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UNCLASSIFIED

SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 6, NDRC

VOLUME 3

A SUMMARY OF ANTISUBMARINE WARFARE OPERATIONS IN WORLD WAR II

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 6
JOHN T. TATE, CHIEF

WASHINGTON, D. C., 1946

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

- Division A — Armor and Ordnance
- Division B — Bombs, Fuels, Gases, & Chemical Problems
- Division C — Communication and Transportation
- Division D — Detection, Controls, and Instruments
- Division E — Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

- Division 1 — Ballistic Research
- Division 2 — Effects of Impact and Explosion
- Division 3 — Rocket Ordnance
- Division 4 — Ordnance Accessories
- Division 5 — New Missiles
- Division 6 — Sub-Surface Warfare
- Division 7 — Fire Control
- Division 8 — Explosives
- Division 9 — Chemistry
- Division 10 — Absorbents and Aerosols
- Division 11 — Chemical Engineering
- Division 12 — Transportation
- Division 13 — Electrical Communication
- Division 14 — Radar
- Division 15 — Radio Coordination
- Division 16 — Optics and Camouflage
- Division 17 — Physics
- Division 18 — War Metallurgy
- Division 19 — Miscellaneous
- Applied Mathematics Panel
- Applied Psychology Panel
- Committee on Propagation
- Tropical Deterioration Administrative Committee

NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a Division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

Any great cooperative endeavor must stand or fall with the will and integrity of the men engaged in it. This fact held true for NDRC from its inception, and for Division 6 under the leadership of Dr. John T. Tate. To Dr. Tate and the men who worked with him — some as members of Division 6, some as representatives of the Division's contractors — belongs the sincere gratitude of the Nation for a difficult and often dangerous job well done. Their efforts contributed significantly to the outcome of our naval operations during the war and richly deserved the warm response they received from the Navy. In addition, their contributions to the knowledge of the ocean and to the art of oceanographic research will assuredly speed peacetime investigations in this field and bring rich benefits to all mankind.

The Summary Technical Report of Division 6, prepared under the direction of the Division Chief and authorized by him for publication, not only presents the methods and results of widely varied research and development programs but is essentially a record of the unstinted loyal cooperation of able men linked in a common effort to contribute to the defense of their Nation. To them all we extend our deep appreciation.

Vannevar Bush, Director
Office of Scientific Research and Development

J. B. Conant, Chairman
National Defense Research Committee

[redacted]

FOREWORD

This report, constituting Volume 3 in the Division 6 Summary Technical Report series, presents a unified summary of the events and problems of antisubmarine warfare, and illustrates how scientific evaluation of naval operations may be accomplished. The report was prepared by the Operations Evaluation Group [OEG], formerly the Operations Research Group [ORG], in the Headquarters of the Commander-in-Chief, U. S. Navy.

This group of civilian scientists, mathematicians, and statisticians was established early in 1942 to function under the supervision of the Atlantic Fleet antisubmarine warfare officer, Captain (later Rear Admiral) W. D. Baker.

When Captain Baker requested the formation of the Group, he stated that the antisubmarine warfare unit, as then constituted, was not in a position to evaluate properly: (1) the probable effectiveness of suggested new weapons; (2) developments and procedures based upon mathematical studies and other available records.

Captain Baker defined what was desired and intended by quoting from a RAF Coastal Command memorandum on the subject, as follows:

> Experience over many parts of our war effort has shown that such analysis can be of the utmost value, and the lack of such analysis can be disastrous. Probably the main reason why this is so, is that very many war operations involve considerations with which scientists are specially trained to compete and in which serving officers are in general not trained. This is especially the case with all those aspects of operations into which probability considerations and the theory of errors enter. Serving officers of the highest caliber are necessarily employed in important executive posts, and are therefore, not available for *detailed* analytic work.

As to the type of personnel required to staff these operations, Captain Baker quoted from the same memorandum:

> A considerable fraction of the staff of an operational research section should be of the very highest standing in science, and many of them should be drawn from those who have had experience at the Service Technical Establishments. Others should be chosen for analytic ability, e.g., gifted mathematicians, lawyers, chess players, etc. An ORS which contents itself with the routine production of statistical reports and narratives will be of very limited value. The atmosphere required is that of a first class pure scientific research institution, and the caliber of the personnel should match this. All members of an ORS should spend part of their time at operational stations in close touch with the flying personnel, and where possible, should occasionally go on operational or training flights.

That the project should be undertaken and the proposed group established in the Navy was never questioned. The experience of the British and of large American industries in carrying on very similar operational analyses made certain that a suitably staffed group could be very effective. The project was assigned to Section C-4, NDRC, and under its contract with Columbia University, a staff was recruited.

Professor P. M. Morse, of the Massachusetts Institute of Technology, became project supervisor, and Dr. William Shockley was granted a leave of absence from the Bell Telephone Laboratories to act as director of research.

The operations performed by the ASWORG closely followed Captain Baker's conception of how the group could assist the Navy. Also, Professor Morse was able to recruit personnel with qualifications very similar to those specified by Captain Baker. Organizational changes later occurred in both OSRD and the Navy, but these did not alter the Group's objectives.

In the Navy, the Group was transferred from Atlantic Fleet antisubmarine warfare to the Tenth Fleet and in OSRD the Group was transferred from the supervision of Division 6 to the Office of Field Services.

The Division wishes to thank Professor Morse and his staff for writing this report. Since it is largely historical in nature, it provides a background for postwar decisions.

It is impossible to name the long list of Navy officers and some Army officers who gave support to the work of the Operations Research Group and who share credit for its performance. The full list would include many officers at operational bases and stations. However, special acknowledgement should be made of the cooperation and assistance received from Admiral W. D. Baker, Admiral F. S. Low, Chief of Staff, Tenth Fleet, of the U. S. Navy and from the British groups.

John T. Tate
Chief, Division 6

PREFACE

This volume on antisubmarine warfare [ASW] represents a compromise between two major aims, to produce a unified summary of the events and problems of the antisubmarine war on the one hand, and to illustrate the scientific evaluation of naval operations on the other. The approach is fundamentally historical on both accounts, however, since the illustrations of scientific evaluation are taken from various analyses and studies made in connection with antisubmarine warfare during World War II. Great care should therefore be exercised in making predictions concerning the future of ASW from it. There is no guarantee that the antisubmarine measures successful in the past will continue to be adequate in the future.

A clear understanding of the events of World War II, their reasons and consequences, is necessary, however, as background for any decisions which are to be made in the postwar period. It is hoped that this volume may serve to some extent as a convenient reference and source of factual material. One overall conclusion is clearly evident from it: the introduction of new weapons, gear, and tactics has led to a continual interplay of measures and countermeasures in which no other conclusion retains its validity for very long. If this lesson alone is learned from it, the volume will have served a useful purpose.

The general organization corresponds closely to the dual aim described above, with two parts quite different in character. Part I is a historical summary of the progress of enemy submarine operations and Allied antisubmarine operations during World War II. No attempt has been made, however, to give a complete chronology of all events. The point of view is statistical, and every effort is made to describe the progress of World War II in quantitative and objective terms. The data are interpreted in terms of the ever-changing tactical and strategical situation. Accordingly, the historical summary is divided into seven chronological periods, as indicated in the Table of Contents. This division is necessary because of the radical changes in the nature of the U-boat war due to changes in U-boat tactics and the introduction of new weapons and countermeasures.

The periods were chosen in such a way that U-boat strategy and tactics were fairly homogeneous in each. The tactics of individual U-boats varied considerably, however, from the typical characteristics which were common to the operations of most of the U-boats during the periods in question. In particular the division points between periods are somewhat indefinite and represent the approximate dates at which a majority of the U-boats had made a major change in their methods of operation.

The data for a given period are further divided into three main sections.

1. A chronological narrative of the most important activities and accomplishments of the U-boats and Allied antisubmarine forces.

2. A more detailed account of the main Allied countermeasures to the U-boats, subdivided into
   a. Convoys
   b. Aircraft
   c. Scientific and technical
   d. Sinkings of U-boats.

3. A survey of the results achieved during the period, from both the U-boats' and the Allies' point of view. This section attempts to explain the reasons for the new tactics which characterize the new period.

Part II of the volume is a more detailed analysis of certain of the major problems of ASW, in particular those which were the subject of operations research studies. The emphasis is on the evaluation of tactics and matériel both by theoretical analyses and by special studies of operational data. Although the principles of ASW derived from such evaluation are strictly applicable only to the situation which obtained during World War II, the methods of evaluation are of more general interest.

The U-boat war spread over all the oceans of the world, but the main battle was fought in the Atlantic. Consequently U-boat activity in other regions has not been discussed as completely as the Battle of the Atlantic. A standard subdivision into areas, which has been used throughout the text, is given in the frontispiece.

There are, in fact, many aspects of the war which are omitted from the discussion. The operations of midget submarines and small battle craft are generally excluded, since they are not considered U-boats. The importance of the training of personnel and developments along this line are not considered. The activities of Naval Intelligence in obtaining information upon which operations are planned are not de-

scribed in any detail. The indirect effects of factors such as strategic bombing are largely neglected. The net result is to limit the discussion fairly closely to Navy antisubmarine operations, though Royal Air Force Coastal Command aircraft and those of the United States Army Air Forces are included when flying antisubmarine missions. The distinction is not a hard and fast one.

The sources of material used are so widely scattered through correspondence and informal memoranda that it has not been practical to quote references to them.

In addition, numerous letters, notes, informal memos, and even oral conversations go to make up the background of this volume. One of its chief aims has been to set down in writing a fair sample of this store of material, whose previous status verged on that of folklore.

No effort has been made, therefore, to assign credit for the work discussed. It originates with various members of British and United States operations research groups, military services, and civilian war agencies. We have tried to collect available information and tell a reasonably unified story, not of the accomplishments of a particular group, but of the progress of a special type of naval warfare.

C. M. Sternhell
A. M. Thorndike
Editors

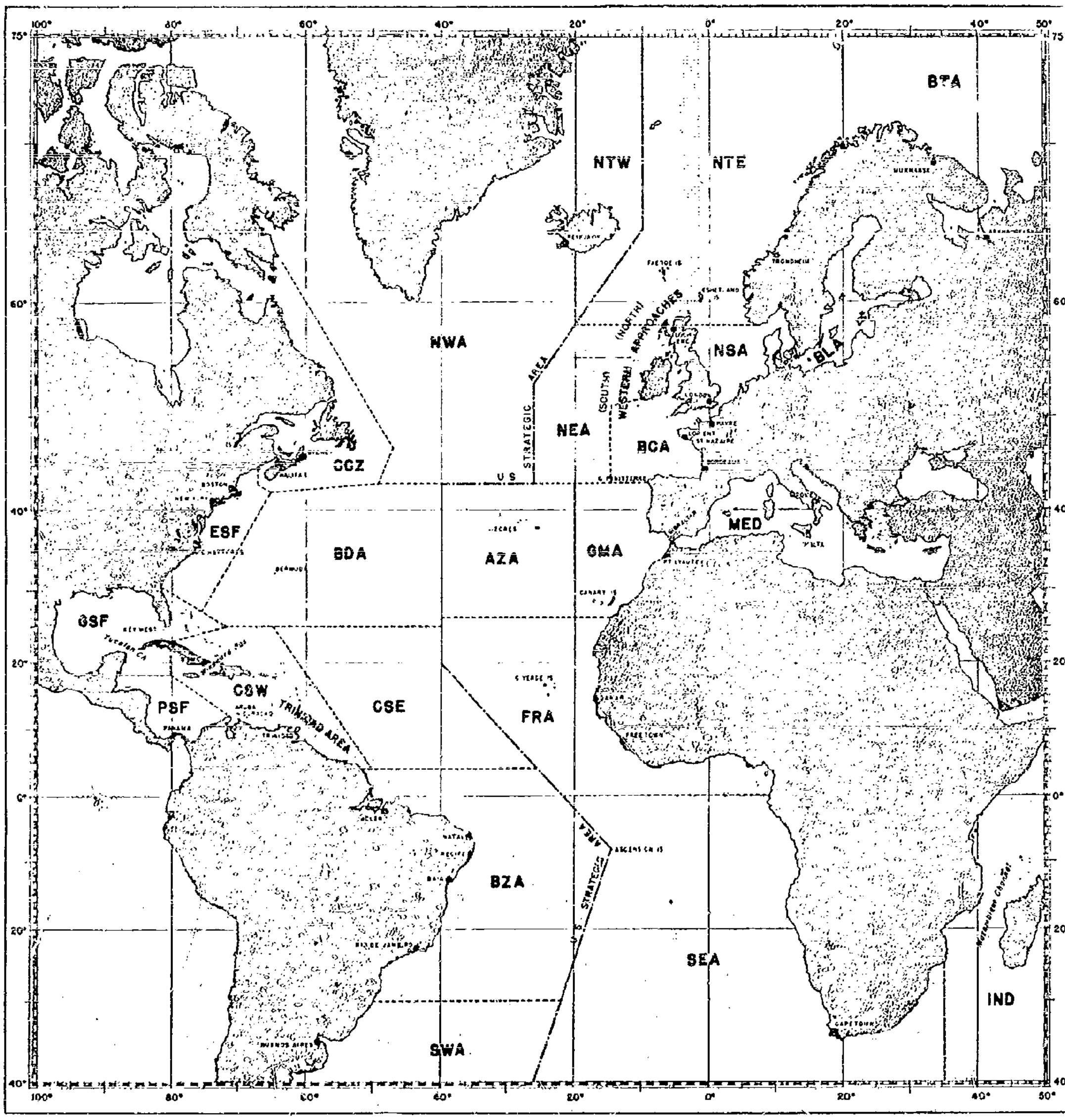
CONTENTS

PART I

HISTORY OF ANTISUBMARINE OPERATIONS

PART II

ANTISUBMARINE MEASURES AND THEIR EFFECTIVENESS



Ocean Areas Referred to in the Text

AZA	Azores Area	CSW	Caribbean Sea Frontier—West	NSA	North Sea Area
BCA	Biscay Channel Area	ESF	Eastern Sea Frontier	NTE	Northern Transit Area—East
BDA	Bermuda Area	FRA	Freetown Area	NTW	Northern Transit Area—West
BLA	Baltic Area	GMA	Gibraltar Morocco Area	NWA	Northwest Atlantic Area
BTA	Barents Sea Area	GSF	Gulf Sea Frontier	PSF	Panama Sea Frontier
BZA	Brazilian Area	IND	Indian Ocean	SEA	Southeast Atlantic Area
CCZ	Canadian Coastal Zone	MED	Mediterranean Red Sea Area	SWA	Southwest Atlantic Area
CSE	Caribbean Sea Frontier—East	NEA	Northeast Atlantic Area		

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PART I
HISTORY OF ANTISUBMARINE OPERATIONS

SUBMARINES IN WORLD WAR I

THE GREAT CAPABILITIES of the submarine as a weapon of war were first revealed during World War I when the U-boat campaign almost proved decisive. Fortunately, the Germans themselves did not fully realize in 1914 how valuable the U-boat's ability to submerge and escape detection would be for offensive operations against enemy shipping. The small number of U-boats available to the Germans were used at first only to attack naval ships and it was not until 1915 that a concerted attack was begun on English merchant shipping.

During 1915 and 1916 there were on the average only about 15 U-boats at sea at any time. These U-boats were sinking about 200,000 gross tons of shipping a month, while about 1½ U-boats were being sunk each month. This situation was extremely satisfactory to the Germans, as the average life of a U-boat at sea during this period was about 10 months, during which the U-boat would sink about 13,000 gross tons of shipping a month, for a total of 130,000 gross tons of shipping sunk before the U-boat itself was sunk.

Encouraged by these successes, the Germans in February 1917 started a large scale campaign of unrestricted warfare on merchant shipping in an attempt to blockade England. This attempt almost proved successful as Allied shipping losses rose steadily to a peak in April 1917. Four hundred and forty-four ships of about 900,000 gross tons were sunk by U-boats during that month. The British Fleet was confined to its bases for there was only 8 weeks' supply of fuel oil in England. Various countermeasures had been tried without success and defeat seemed just around the corner unless an antidote to the U-boat could be found.

INTRODUCTION OF CONVOYING

Admiral Jellicoe was brought to Admiralty to deal with the situation. The convoy system, twice turned down on account of lack of escort vessels and loss of time to shipping, was introduced in April 1917 and proved immediately successful in reducing the shipping loss rate. The result of all the various British countermeasures, of which the convoy system was the most effective, was that by October 1917, 1501 ships in 99 convoys had been brought into port with the loss of only ten ships sunk while in convoy (a loss rate of less than 1 per cent).

LACK OF SATISFACTORY COUNTERMEASURES

Although shipping losses had been checked, it should be kept in mind that, from an offensive point of view (i.e., destruction of U-boats), the U-boat had not been definitely beaten in World War I. After the start of unrestricted U-boat warfare early in 1917, the Germans maintained an average of about 40 U-boats at sea at any time. During this period the average number of U-boats being sunk each month was only about seven; the maximum number of U-boats sunk in any month was only 14 in May 1918. Therefore, the average life of a U-boat at sea during the last year of World War I was still about 6 months. Shipping losses, even during the last year of World War I, were still running at the level of about 300,000 gross tons a month, so that at that time each U-boat was still sinking about 15,000 gross tons before it, itself, was sunk.

These figures indicate that other factors besides U-boat losses must have contributed to the mutiny of U-boat crews in 1918, as the rate of U-boat losses has reached far higher levels in World War II without any corresponding crack-up in morale. Another point to be considered is that a large part of German U-boat losses in the latter part of World War I was due to mines, whose effectiveness was greatly increased by the fact that the geographical position of the German U-boat bases necessitated passage through the North Sea. Of the 178 U-boats sunk during the first World War, about 45 per cent were sunk by surface craft, about half of these by depth charges and half by gunfire and ramming. About 30 per cent were sunk by mines, another 10 per cent were torpedoed by submarines, and the other 15 per cent by other causes. It is therefore clear that the Allies had not developed any offensive weapon during World War I which could deal so effectively with the U-boat at sea that further operations would not be profitable.

That the Germans themselves still thought the U-boat was an effective weapon at the end of World War I may be seen from the fact that there were about 220 U-boats under construction in November 1918. Admiral Scheer's building program of October 1, 1918 provided for at least 30 U-boats a month beginning the middle of 1919 and would probably have been fulfilled if hostilities had continued. If the war had not ended in November 1918, the Allies would have had to face a second and more intensive U-boat campaign.

NEED FOR SCIENTIFIC AND TECHNICAL ADVICE

One of the most significant points about antisubmarine warfare which became apparent early in World War I was the necessity of having scientific and technical aid in combatting the U-boat. The essential problem was that of having some means of detecting a submerged U-boat and then of having some weapon that would provide a good chance of destroying the U-boat.

The first crude attempt to develop an instrument to detect the submerged U-boat resulted in the installation of hydrophones on Allied naval ships in 1915. The hydrophone was simply an instrument for listening to the noise produced by the submarine, and sonic frequencies below 10 kc were used. No range and only a rough bearing were obtained from these early hydrophones and it was impossible to make attacks on U-boats with any degree of precision. The main effect of hydrophones was on U-boat morale, as U-boats found that they were being followed after diving instead of being free of their pursuers.

The first depth charges to be used in attacking submerged U-boats were also introduced in 1915. However, so few were available that the Germans did not realize they were being used until 1917.

In September 1918 the British formed a small committee, consisting largely of scientists, called the Anti-Submarine Division International Committee (the initials spell ASDIC, the name given by the British to their echo-ranging detector). This committee developed a method of transmitting sound of supersonic frequencies under water and then using the echo returning from the submerged submarine to fix its position. Although the Asdic set was still in the experimental stage when World War I ended, the labors of the committee were not wasted, as effective underwater echo-ranging gear was developed in the 1930's and proved to be quite a surprise to the Germans at the start of World War II. Due to the ability of Asdic to provide both range and bearing, it proved far better than the hydrophones used in World War I. Hydrophones, themselves, were also improved by using supersonic frequencies and making them directional, thereby enabling the operator to obtain more accurate bearing.

ORDER OF BATTLE—SEPTEMBER 1939

At the start of World War II, England had only about 220 Asdic-fitted antisubmarine craft consisting of approximately 165 destroyers, 35 patrol craft (*i.e.*, sloops, frigates, corvettes) and 20 trawlers. This total may be compared with the more than 3000 ships (about 450 destroyers, 170 patrol craft and the remainder trawlers and small craft) available to the Allies for antisubmarine warfare in 1918.

The British, profiting from their experience in World War I, had learned that the ocean convoy system did more than anything else to reduce shipping losses. They knew that the convoy system works best in open water where evasion can be employed and that its success depends upon efficient escorts armed with effective offensive weapons. They were also aware of the fact that an efficient U-boat tracking system is necessary to practice effective evasion and a daily U-boat plot based on contacts, DF fixes, and intelligence was used throughout the war.

Meanwhile the Germans had done considerable research in developing and improving their U-boats. The U-boats available to the Germans at the start of World War II were faster than those used in World War I and were also considerably stronger, being able to dive deeper and to withstand more depth-charge punishment. The Germans had also developed an electric torpedo which left no visible wake.

However, in September 1939, the Germans seem to have had available only about 60 U-boats, of which 30 were of the small 250-ton type (of limited endurance—suitable for coastal operations only) and 30 of the larger ocean-going type, 20 of which were of 500 tons and 10 of 750 tons. This small number suggests that Germany, possibly not anticipating that England would enter the war at that early date, had given higher priorities to the building of tanks and aircraft for land warfare than to the building of U-boats.

Chapter 1

FIRST PERIOD

SUBMERGED DAYLIGHT ATTACKS ON INDEPENDENTS

SEPTEMBER 1939–JUNE 1940

1.1 U-BOAT OFFENSIVE

This first phase of U-boat[a] warfare was greatly influenced by the rapidly changing overall military situation. Germany invaded Poland on September 1, 1939, and England and France declared war on Germany on September 3. Some U-boats had left Germany early in August and when the war began there were about six at sea, ready to start an offensive in the Northeast Atlantic in the Western Approaches to England.

According to statements of early prisoners of war, the commanding officers of U-boats had been ordered to observe International Law, which forbade U-boats to sink merchant vessels without having first placed the passengers and crew in a place of safety. At the beginning of September, these instructions seem to have been generally obeyed, with the notable exception of the *Athenia*, which was torpedoed without warning on September 3. However, this situation did not last long and, toward the end of September, even neutral ships were being torpedoed without warning.

Anticipating unrestricted U-boat warfare, the British had prepared plans before the war for the immediate establishment of the convoy system and the first trade convoy sailed on September 6. As the British defenses against U-boat attacks were based on the needs of protecting primarily the fleet and secondarily merchant shipping, the limited number of antisubmarine vessels available for convoy escort was inadequate to provide direct protection to the convoys. Nevertheless, it was believed that the British antisubmarine measures were sufficiently effective to ensure that no U-boat could betray her presence by attacking a convoy without running a severe danger of subsequent destruction by the escorting craft.

The experience during September tended to justify these expectations, as over 900 ships were convoyed during the month without the loss of a single ship while in convoy. In addition, two U-boats were sunk during the month by British surface craft. The Germans apparently had no knowledge of British Asdic and still believed that they could counter underwater detection by reducing internal noises.

The lack of knowledge of British Asdic probably accounted for the early U-boat tactics. The U-boats preferred attacking their targets during the daylight, believing themselves relatively invisible because of their powers of submergence, while they could observe the targets through their periscopes. The U-boat attacks were generally made by torpedo from periscope depth, but if the target was an unarmed merchant vessel, the U-boat usually surfaced and attempted to sink the ship by gunfire.

During September, while the convoy system was still not fully established, there was a sufficient number of unescorted targets at sea to enable the U-boats to sink 39 ships of 151,000 gross tons. Ten of these ships were sunk by gunfire alone, from surfaced U-boats, and this led the British to take immediate steps to arm as many merchant ships as possible to defend themselves against such attacks.

At the start of the war antisubmarine forces in the Western Approaches were augmented by aircraft carriers, but after HMS *Courageous* was sunk by U-boat torpedoes on September 17, the carriers were withdrawn. However, shore-based aircraft of the Coastal Command helped considerably by flying over 100,000 miles in September, sighting some 50 U-boats or supposed U-boats, and attacking over 30 of them. Although none of the aircraft attacks were very effective, they did cause the U-boats to submerge and thereby reduced their effective operating period.

The September U-boat campaign was followed by a lull during the first ten days of October during which, although U-boats were at sea, hardly any ships were attacked. This lull seemed to reflect the political situation at the time, as it was accompanied by Hitler's offer of peace on October 6. U-boat activity flared up again on October 12, and by the end of the

[a] The term U-boat is used to refer to any *enemy* submarine (German, Italian, Vichy French, or Japanese) with a displacement of 200 tons or more.

month 28 ships of 136,000 gross tons had been sunk by U-boats. In addition Kapitän-leutnant Prien, in command of U-47, penetrated the harbor of Scapa Flow in the middle of October, and sank HMS *Royal Oak*, a British battleship. This served to direct British attention to the necessity of protecting harbors against U-boats by means of fixed defenses, such as booms, indicator loops, mine fields, and harbor defense Asdics.

During November and December the main effort of the German U-boats seems to have centered upon a mine-laying campaign on the East Coast of England, particularly in the Thames Estuary. The mines laid were both the old type of contact mine and a new type of magnetic mine, which at first proved rather difficult to sweep. Monthly losses due directly to U-boats (torpedoes and gunfire) fell to 18 ships of about 65,000 gross tons and were exceeded by the 100,000 gross tons of shipping sunk by mines during each of these months.

U-boat activity began increasing again in the second week of January 1940 and by the end of the month there were as many U-boats at sea as at the start of the war. In February, the U-boat effort was greater than during any previous period and 35 ships of 153,000 gross tons were sunk. The U-boats continued to follow a policy of attacking Allied and neutral ships without warning. They preferred attacking single ships or stragglers from convoys, thus making it difficult for the antisubmarine ships to conduct an effective search and counterattack. The respect the U-boats had been showing for the British convoys is indicated by the fact that only 7 of the 169 ships sunk by U-boats during the first six months of the war were in convoy when sunk, although roughly half the shipping sailed in convoy at this time.

Losses due to mines fell off during January and February as better methods of sweeping the magnetic mines were developed and more ships were degaussed (magnetic field of ship changed to protect it against magnetic mines).

There was a marked lull in U-boat activity throughout March, featured by the complete absence of U-boats from Atlantic waters after about the 12th of the month. Early in April, every available U-boat left Germany to take up patrol positions in the North Sea to help in the impending military operations against Norway. The average number of U-boats at sea reached a peak of about 15 during the second week of April, when Germany invaded Norway. Despite the large concentration of U-boats, the damage done by them was remarkably small. No British capital ship was even attacked by U-boats and only six ships of 31,000 gross tons were sunk by the U-boats during the whole month of April, a new low for the war. In addition, the Germans lost six U-boats during the month, a new high for the war.

There was very little U-boat activity during the first half of May as Germany started her invasion of Holland and Belgium on May 10. It is believed that during May no U-boat proceeded to the Western Approaches until the 21st and only 10 ships of 48,000 gross tons were sunk by U-boats during the month. Shipping losses to U-boats were exceeded for the first time during the war by the 154,000 gross tons sunk by aircraft. These losses were incurred largely in connection with the operation and evacuation of the British Expeditionary Force, which left Dunkerque on May 29.

The Germans announced on May 29 that U-boat warfare was about to recommence and warned neutrals not to enter the protection of British convoys. This threat was followed by a period of intense U-boat activity as convoys were attacked with greater boldness than in earlier periods, advantage being taken of the paucity of escorts, rendered inevitable by the demands of the military evacuation and the Home Fleet. The losses for June were the highest of the war, with 56 ships of 267,000 gross tons being sunk by U-boats. The German ace, Klt. Prien, contributed his share by sinking ten ships of about 67,000 gross tons during one cruise. By the end of June, France was out of the war and Italy had entered the war with over 100 U-boats, about 60 of which were ocean going (650 tons and over).

1.2 COUNTERMEASURES TO THE U-BOAT

1.2.1 Convoys

The convoy system was by far the most effective countermeasure in keeping down shipping losses to U-boats during this first period, just as it had been during World War I. This was still true, even though the number of antisubmarine vessels suitable for ocean escort was insufficient to provide direct protection to the convoys. The British met this problem by keeping their convoy system flexible, changing the number of escorts and the distances for which con-

voys were escorted in accordance with U-boat activity. It should be noted that the Germans made this problem more difficult by sending the U-boats out in waves, so that peaks of U-boat activity occurred in September 1939 and in February and June of 1940.

Although the first convoys sailed early in September 1939, the convoy system was not fully in force until the beginning of October. The designations of the main convoy routes that were set up then were:

- OB Outward bound from England to America and Africa.
- HX Homeward bound to England from Halifax.
- SL Homeward bound to England from Sierra Leone.

In order to illustrate some of the problems involved in setting up the convoy system a detailed account is presented of the changes made in the HX convoy route during this period. On October 7, 1939, it was decided to discontinue the convoys from Kingston, Jamaica, and all ships in the West Atlantic were routed independently to Halifax, taking advantage of U. S. waters as far as possible. Convoys were divided into slow (9- to 12-knot) and fast (12- to 15-knot) convoys, which left Halifax at about the same time in order to arrive four days apart at the rendezvous point. At this point, located at about 15° west longitude, the convoys were met by one or two destroyers which provided antisubmarine escort to England. The ocean escort, provided between Halifax and the rendezvous point primarily for protection against surface raiders, consisted of a battleship, cruiser, or armed merchant cruiser, and one or two submarines when available.

The first of these convoys, HX 6 and HXF 6, consisted of 62 and 6 ships, respectively. The dividing line was then altered to 11 knots to equalize the number of ships, and during November 1939 the number of ships in these sections averaged 32 and 12. On February 12, 1940, the fast convoys were discontinued, and all HX convoys sailed at 9 knots, at 3- and 5-day intervals. These convoys consisted of ships with speeds between 9 and 15 knots, ships of higher speeds sailing independently. At the beginning of April, in order to equalize the size of the convoys, 4-day intervals were started.

Early in May 1940 Bermuda began to be used as an assembly point for vessels from the West Indies and other points in that vicinity, and HX 41 was the first combined Bermuda and Halifax convoy. The sections formed at sea, as arranged, at about 41° north latitude and 43° west longitude, and the Bermuda escort then returned to base. This change enabled about 60 per cent of the ships that formerly sailed from Halifax to cut down their voyage by 500 miles and to avoid the fog off Newfoundland. The average number of ships in these HX convoys had risen to 46 by May 1940.

In addition to the above-mentioned convoys, the British also sailed coastal convoys to protect shipping on short trips around the English coast and Scandinavian convoys to and from Norway. The main energies of the French light craft were also devoted to the protection of merchant shipping. They were fitted with Asdic as soon as possible after the opening of the war and provided escorts for purely French convoys, helped escort the Gibraltar convoys for most of the way, and assisted in covering the military cross-Channel convoys.

The extreme value of the British convoy system may best be appreciated by noting that during this period about 2500 ships were being convoyed monthly, while only about 5 of these were being sunk monthly by U-boats (2½ in escorted convoys, 1½ in unescorted convoys, and 1 straggler). The rate at which independent merchant vessels were being sunk by U-boats was roughly about four times as high.

1.2.2 Aircraft

Another important countermeasure to the U-boat was the use of aircraft. These had seen very little use against U-boats during World War I and consequently it took some time before the problems of how to use aircraft most efficiently against U-boats were solved. In addition, the aircraft were still armed only with bombs. Consequently the direct contribution of aircraft toward sinking U-boats was negligible during this period.

Nevertheless, aircraft performed a defensive function of great value in helping to protect shipping. Coastal Command aircraft flew, on the average, about 4500 hours monthly on purely antisubmarine work. About 20 U-boats were sighted monthly and 12 of these were attacked, with about 10 per cent of the attacks resulting in some damage to the U boat. This effort reached a peak of 9500 hours during June 1940, when about 2800 hours were spent on antisubmarine patrol and 6700 hours on convoy escort duty.

The main value of this flying was in causing the U-boats to submerge, thus preventing them from shadowing or approaching convoys on the surface. It also helped to discourage them from operating close to the shores of England where the flying was heaviest. U-boats at this time were under orders to submerge as soon as they sighted a plane and the British took advantage of this by starting to use, in November 1939, light aircraft of the Moth type to patrol around the coast. These aircraft were known as "scarecrows," carried no bombs, and were used solely to sight and report U-boats, and to make them submerge. These flying hours and sightings also helped considerably in keeping an accurate U-boat plot.

1.2.3 Scientific and Technical

Applying the lessons learned in World War I, considerable scientific work was being done during this period to improve antisubmarine attacks. Some of the typical problems being investigated then were:

1. Development of an Asdic receiver-amplifier with automatic sensitivity control so that both long and short range echoes would be clearly recorded.

2. Theoretical investigation of improved methods of carrying out antisubmarine attacks and of the best type of depth-charge pattern to ensure destruction of the submarine.

3. Assistance to antisubmarine personnel in distinguishing between submarine and non submarine targets, as a great amount of effort and a large number of depth charges were being expended on wrecks, whales, and other non submarine targets.

1.2.4 Sinking of U-Boats

Surface craft, equipped with Asdic and depth charges, were by far the most potent enemy of the U-boat during this first phase of U-boat warfare. Twenty-one German U-boats are known to have been sunk[6] as a result of Allied action during this 10-month period; 15 were sunk by surface craft, one by the coordinated action of two ships and one plane, one by a plane from a British battleship, two were torpedoed by submarines, and two were mined in attempting to pass through the Dover Barrage in October. Two other German U-boats were sunk under unknown circumstances while one is known to have been sunk in the Baltic after being rammed accidentally.

In addition to the 24 German U-boats mentioned above, 10 Italian U-boats were sunk in the Mediterranean, Red Sea, and Indian Ocean between June 10, when Italy entered the war, and the end of the month.

1.3 SURVEY OF RESULTS

1.3.1 From the U-boat Point of View

The average number of U-boats at sea in the Atlantic during this first phase of the U-boat war was about six. The average number of ships sunk monthly by them was 26 of about 106,000 gross tons, so that about four ships of about 18,000 gross tons were being sunk per U-boat month at sea. However, about two out of the six U-boats at sea were being sunk each month, so that the average life of a U-boat at sea was only about three months. This relative rate of loss of U-boats was extremely high, much higher than at any stage of the first World War, and makes readily understandable the fact that they preferred attacking unescorted ships to attacking convoys, lightly escorted as they were. It also helps to explain why the German U-boats felt it necessary to change their tactics during the next phase of the U-boat war; this, despite the fact that the overall exchange rate (*i.e.*, 13 ships of about 53,000 gross tons sunk for each U-boat sunk) might be considered satisfactory for the U-boats. The rate of loss of U-boats simply was higher than the Germans could afford.

The fact can be clearly seen from another approach. The Germans started the war with about 30 ocean-going U-boats (*i.e.*, 500 tons or larger). By the end of June 1940, 18 of these had been sunk while only about 15 new ones had been commissioned, so that the Germans only had about 27 ocean-going U-boats available at the start of the second period of the U-boat war.

1.3.2 From the Allies' Point of View

At the end of June 1940 England was left alone in the war against Germany and her ability to carry on the war was dependent on her keeping her sea lanes open. Total shipping losses of the Allied and neutral

[6] The estimates given here for U-boat sinkings are based on Allied assessments. Incidents assessed A or B are considered to have sunk the U-boat. Justification for this assumption is given in Appendix I.

nations were about 280,000 gross tons monthly as compared to a building rate of only about 88,000 gross tons monthly, for a total net loss of 1,920,000 gross tons due to all causes during this 10-month period out of a total of about 40,000,000 gross tons of shipping at the start of the war. It appeared that shipping losses were still on the upgrade and the only hope of keeping the rate of net loss down was a large increase in shipbuilding.

Of the 280,000 gross tons of shipping lost monthly, about 223,000 gross tons were lost by enemy action, with U-boats accounting for 106,000 gross tons or 48 per cent of the total lost by enemy action. Mines accounted for 58,000 or 26 per cent, aircraft for 27,000 or 13 per cent, surface craft for 14,000 or 6 per cent, and other and unknown causes for the other 7 per cent of the losses.

The U-boat appeared definitely to be the main threat to Allied shipping. The convoy system had been the main factor in keeping the shipping losses due to U-boats down to a moderate level. Although the number of British Asdic-fitted antisubmarine vessels increased from about 220 at the beginning of the war to about 450 at the end of June 1940, most of the increase took place in trawlers and other small ships. The 450 ships consisted of about 180 destroyers, about 55 patrol craft, and about 215 trawlers and other small craft. However, the number of these ships that could be spared for escort duty was still insufficient to provide adequate protection to the convoys. The British had been fortunate during the first period that the enemy had only a small number of U-boats available and these had operated in a limited area, almost all the sinkings of ships occurring in the Northeast Atlantic (east of 20° west longitude and north of 30° north latitude). This had helped to make the escort problem easier during the first period.

Chapter 2

SECOND PERIOD

NIGHT SURFACED ATTACKS ON CONVOYS

JULY 1940–MARCH 1941

2.1 U-BOAT OFFENSIVE

THE SECOND PHASE of the U-boat war was marked by a complete change in enemy tactics. The Germans, having discovered as a result of their high rate of loss that the U-boats were quite vulnerable to Asdic when submerged, decided to make use of the hours of darkness to regain their relative invisibility. At night, trimmed down on the surface, a U-boat offers a very small target to the human eye and is also rather difficult to detect by Asdic. The surfaced U-boat has the advantage of high speed and maneuverability and therefore has good chances of avoiding detection by the escorts. Acting on this principle and encouraged by the results achieved at night during the first period by a few of the more successful U-boat captains, the U-boats started, in July 1940, the general practice of attacking convoys at night from a surfaced position and then using their high surface speed to escape. Occasional daylight attacks were still made on ships sailing independently, and on stragglers from convoys.

Accompanying this change in the enemy's tactics came the occupation of the French ports and their establishment as U-boat bases, marked by the first visit of a U-boat to Lorient on July 22. The use of French bases served to cut down the transit time of the U-boats and enabled them to extend their area of operations further westward in the Atlantic. From his air bases in France, the enemy was also able to send out long-range reconnaissance aircraft to pick up convoys in the Atlantic.

In addition, after the fall of France there developed the threat of a sea-borne invasion of England. This confined a large number of destroyers to the East and South coasts of England and consequently, as the number of ships available for convoy escort was necessarily limited, the U-boats were encouraged to attack convoys more frequently. Aircraft were also diverted from antisubmarine patrols over the Western Approaches to England, where the U-boats were operating, to anti-invasion patrols to the eastward.

Some Italian U-boats had also started operation in the Atlantic in August 1940. These Italian U-boats used Bordeaux as a base and followed the same methods as German U-boats, presumably working directly under German orders. Their operational areas were usually southward of the ones used by the German U-boats.

Increased U-boat activity, which had commenced in June 1940, continued throughout July and August with over 200,000 gross tons of shipping being sunk in each of those months. Up to the middle of July, the most active area was still the Western Approaches between the latitudes of 48° north and 51° north. After the threat of air attack from French bases had led to the rerouting of British convoys around the north of England, the U-boats lost no time in shifting their area of activity to the Northwestern Approaches to meet the increased traffic there. This activity was marked by increased attacks on convoys while antisubmarine escorts were actually present, but these attacks were generally on large convoys which, owing to the shortage of escort vessels, were guarded by only about two Asdic-fitted ships.

On August 15 Germany proclaimed a complete blockade of the British Isles and called upon neutral governments to forbid their ships to sail through the Anglo-German war zone. U-boat activity was considerably intensified after that date and the shipping losses continued to increase, with about 300,000 gross tons being sunk by U-boats in September, and a new high for the war was reached in October when 62 ships of 346,000 gross tons were sunk by U-boats. The scene of greatest activity during these months was still the Northwestern Approaches, with night attacks on convoys being the most favored method of attack by the U-boat. Of the 59 ships attacked in this area in September, 40 were in convoy; 71 per cent of the total were night attacks. The concentration of aggressive operations into the period of, and immediately following, the full moon was especially notable during October when 3? ships were attacked on October 18 and 19.

It should be kept in mind that during these months of heavy losses the average number of U-boats at sea was still only about six. This means that ten ships of about 60,000 gross tons were sunk by the average U-boat at sea during October 1940, probably an all-time high in operating efficiency for submarines. In addition to inflicting these heavy losses, the U-boats were almost invariably escaping unscathed, as, for example, in October when only one U-boat was sunk in the Atlantic. These were the days when the star German commanders (U-boat aces) such as Prien and Kretschmer were operating. These aces had survived the hazards of operating during the first period and had profited from the experience gained then. The U-boats making these night attacks on convoys were operating individually and usually only one or two U-boats would be involved in the attack. Despite this, some of the convoys suffered rather heavy losses, as, for example, HX 79, which lost 12 ships to two U-boats in one night in October.

The normal procedure for U-boats attacking convoys at this time seems to have been as follows: The U-boat gained contact with the convoy during the day, either as a result of reports from long-range German reconnaissance aircraft, reports from other U-boats, or by sighting smoke, and then proceeded to shadow the convoy at visibility distance on the bow or beam. When darkness had fallen, the U-boat, trimmed down on the surface, closed the convoy, and endeavored to reach a position broad on its bow. She kept very careful watch for the escorts and endeavored to pass astern of those stationed on the bow of the convoy. The approach was pressed home as close as the U-boat captain dared, and it is possible that, in some cases, a firing range of about 600 yards was achieved. Having reached a firing position on the beam of the convoy, most U-boats increased to full speed, fired a salvo of four torpedoes, turned away still at full speed, firing stern tubes if possible, and retired as rapidly as possible on the surface in the direction considered safest. If their retreat was unseen, they might reload their torpedo tubes on the surface and attack again in the same manner later in the night.

The serious damage inflicted on British convoys by these new U-boat tactics caused a considerable number of changes to be made in the convoys. The spacing of the convoy columns was opened up to reduce the chance of more than one ship's being hit by a salvo. Escorts were stationed farther away from the convoy and new plans were developed for searching for the U-boat with illuminants following attack. To improve the tactical efficiency of the escorts, these ships were formed into groups and as far as possible ships of one group were to work together. Admiralty took over the responsibility for the routing of all ocean-going convoys, thus enabling emergency changes to be made without delay. In addition, great efforts were made to equip all convoy escorts with radar, which would enable them to locate U-boats on the surface at night outside visibility distance and possibly before they could attack the convoy.

By November 1940 Lorient had become the principal U-boat base and during this month one German U-boat had left this port and gone as far south as Freetown, sinking four ships in three days. November was also marked by several heavy air attacks on the ports of Lorient and Bordeaux, which were considered to have inflicted severe damage on both U-boats and their bases.

The first known successful counterattack against the German method of night attack on convoys occurred on November 21 after two ships of convoy OB 244 had been torpedoed. The British corvette HMS *Rhododendron*, stationed astern as a rescue ship, sighted an object momentarily at a range of 1500 yards about an hour after the torpedoing. Three minutes later Asdic contact was gained and then depth charges were dropped with the result that considerable metallic wreckage and oil were blown to the surface.

This successful counterattack, plus the loss of two other U-boats, might account in part for the reduced number of attacks on escorted convoys in November and December 1940. Heavy winter weather in the North Atlantic was probably also a factor in accounting for the decrease in shipping losses to U-boats, as only 150,000 gross tons were sunk in November and 200,000 gross tons in December.

Early in December a westerly movement of the U-boats became noticeable, with most of them stationed as far out as 20° west longitude. This may have been due in part to Coastal Command flying and in part to an attempt to intercept incoming convoys before the antisubmarine escort joined. However, this actually increased the enemy's difficulty in locating convoy traffic.

As a counter to the fact that U-boats in the Northwestern Approaches had been attacking British convoys in longitudes 20° to 25° west, which is an area

beyond the point which could be reached by the escorts new evasive routing measures were adopted in December. It was decided to make use of dispersion to the maximum extent that the endurance of merchant ships permitted, and the routes of the convoys were spread between 63½° and 57° north latitude. The cycles of convoys were also opened out, with the object of reducing the strain on escorting forces.

This thorough diversion of convoy routes seems to have been the main factor in the reduction of shipping losses, just as it had been in World War I. No attacks were made on escorted convoys from December 1940 until January 29, 1941, and the shipping losses to U-boats in January dropped to 21 ships of 127,000 gross tons, the lowest figure since the Germans announced their intensified U-boat campaign in May 1940. This occurred despite the fact that the average number of U-boats at sea in the Atlantic had increased to about 12. Most of the ships lost during these two months were not in convoy, since the U-boats had difficulty finding convoys and resorted to the much easier task of picking off stragglers or ships sailing independently.

The month of February 1941 opened with a continuation of the comparative lull in U-boat activity. Evasive routing had frustrated the normal German "hit and run" method of night attack on the convoys. However, it became clear in February that this had provoked intensified enemy offensive measures, in the form of greater cooperation between aircraft and U-boats, and special searching patrols. The days of wolf-pack attacks were foreshadowed as the U-boats started operating in groups of three to five, each U-boat being given a limited patrol area within the wider area covered by the group. The first U-boat to gain contact shadowed the convoy while others were ordered to concentrate in a position to attack. The shadower usually emitted radio signals to home other U-boats or aircraft to the attack. Similarly, aircraft were able to home U-boats to a convoy.

Cooperation between U-boats, aircraft, and surface craft is well illustrated by the attack on HG 53, consisting of 21 ships escorted by one sloop and one destroyer. The convoy was attacked by a U-boat at 0135 on February 9, two ships being sunk. The U-boat continued to shadow the convoy and probably homed six Focke-Wulf aircraft to it during the afternoon of the 9th. Five ships were bombed and sunk while one plane was shot down. The U-boat continued to shadow the convoy and again attacked on the 10th, sinking one ship. After this, she maintained touch with the convoy, reporting its position. Her reports were evidently intended for a German "Hipper" class cruiser. While closing HG 53, this cruiser came upon the unescorted slow portion of SL 64 and directed her attack against this easy target, sinking seven ships.

Three other convoys were attacked by U-boats in the last week of February, and as the month drew to an end, with the losses mounting to 36 ships of 189,000 gross tons, it was evident that the expected spring offensive of the U-boats had commenced. The average number of U-boats at sea in the Atlantic rose to 16 in March and these included some of Germany's most skillful U-boat captains. Their tactics included a repetition of the concentrated night attacks upon convoys, and six convoys were attacked during the month. The upward trend of shipping lost by U-boat action reported in February was maintained during March with the total losses reaching 40 ships of 239,000 gross tons. These losses were considerably less than those recorded during September and October 1940, the last previous period of intense U-boat activity, and were not considered unduly alarming considering the fact that the number of U-boats at sea in March 1941 was more than twice as great as in the earlier period.

More encouraging was the evidence of the increased efficiency of antisubmarine escorts and of the fact that U-boats which attacked adequately escorted convoys could be dealt with effectively. This evidence was clearly demonstrated by the loss to Germany, during March, of her three outstanding U-boat aces (Prien, Kretschmer, and Schepke), the top three U-boat captains in terms of tonnage sunk, each having more than 200,000 gross tons of shipping to his credit.

Prien, commander of U-47, was the first to be lost as a result of his attack on Convoy OB 293 when he sank one ship shortly after midnight on March 8, 1941. HMS *Wolverine*, one of the escorts, sighted smoke about 20 minutes after the attack on the convoy and subsequently made contact with the U-boat. The U-boat was attacked for over five hours, during which time there occurred a remarkable chase of the U-boat on the surface for over an hour, before it was finally considered sunk. There were no survivors but

prisoners of war from U-boats sunk subsequently have supplied information from which it is believed that the *Wolverine's* attacks were made on U-47, commanded by Prien. Berlin subsequently admitted the loss of Prien.

U-100 (Schepke) and U-99 (Kretschmer) were both sunk as a result of the attack on Convoy HX 112, during which five ships were sunk. U-100 located the convoy, which had been reported earlier by U-99, on the evening of March 16. Later she sighted a destroyer astern and dived. At 0137 on the 17th, HMS *Walker* obtained Asdic contact and attacked with depth charges. Three further depth-charge attacks were carried out by HMS *Vanoc* and HMS *Walker* before contact was lost at 0250. Meanwhile U-100, which had been considerably damaged by the depth charging, had surfaced. While the escorts were preparing to take station for an organized search, *Vanoc's* radar operator reported a contact 1000 yards away and U-100 was subsequently sighted on the surface and rammed by HMS *Vanoc*. Schepke, who was caught and crushed between the stove-in side of the bridge and the periscope, was carried down with the sinking U-boat.

While HMS *Vanoc* was picking up survivors of U-100, HMS *Walker* obtained Asdic contact. Although it was considered unlikely that another U-boat would remain so close, the Asdic operator was so convinced that he had a submarine contact that HMS *Walker* fired six depth charges. This attack was extremely accurate and brought U-99 to the surface almost at once. Both destroyers opened fire and U-99 was abandoned shortly afterward, with Kretschmer and other survivors taken as prisoners. Kretschmer had been quite successful up to that point as he claimed a record total of 86,000 tons of shipping sunk on this last cruise, while his total sinkings had reached 338,000 gross tons, more than any other U-boat captain.

There were immediate indications that the enemy was severely shaken by the results of his attacks on adequately escorted convoys. The only subsequent attack during the month was made far west before the antisubmarine escort had joined, when three ships were sunk from HX 115 at 29° west longitude. Beside the effect on the tactics and operations of U-boats, the loss of three of Germany's most skillful U-boat commanders must have had a profound effect on U-boat morale.

2.2 COUNTERMEASURES TO THE U-BOAT

2.2.1 Convoys

The high percentage of hits obtained by U-boats in night attacks made it necessary in November 1940 to increase the distance apart of convoy columns from about 600 yards to about 1000 yards. The distance between ships in the same column was about 400 yards. In December 1940 the distance between columns during the daytime was reduced back to 600 yards to increase protection against air attacks.

To counter the heavy losses suffered as a result of the night attacks by surfaced U-boats in September and October 1940 the escorts were stationed in positions down each wing at a greater distance from the convoy than before. In the event of an attack, they were instructed to proceed outward from the convoy for a distance of 10 miles at full speed, firing star shell to illuminate the area where the U-boat might be, in an attempt to sight her or force her to submerge, thereby improving the chances of Asdic detection. If contact was made, two escorts were to hunt the U-boat, while the remainder were to rejoin the convoy.

Later, when radar equipped escorts became available, they were stationed one on each beam of the convoy, about 4 miles from it in order to avoid back echoes from the convoy on the radar set. The beam escorts were to steam on the same and opposite courses as the convoy, zigzagging as requisite for self-protection. Another method of sweeping, which was under trial in order to effect an economy in fuel, was for the escort to start a slow turn of 360° when in a position abeam of the leading ships, thus sweeping outwards and astern at about 1° per second, and on completion assuming station abeam of the rear ships. The remainder of the escorts were disposed as before, but were instructed to bear in mind that, at night, the rear wing positions were the most important and that, in the event of a U-boat attack, star shell searches were to be made in the rear of the convoy also.

By the beginning of this period, in July 1940, the convoy system was fully established and most of the subsequent changes were made necessary by enemy activity. This may again be illustrated by continuing the history of the transatlantic HX convoys, the main line of supply to England. Besides the serious U-boat

threat, enemy air and surface craft activity also had their effects on these convoys.

The first HX convoy to be routed around the north of England in July 1940 made a rendezvous with the local antisubmarine escort at about 17° west longitude. Slow convoys to include ships between 7½ and 9 knots were organized in August to assemble at Sydney, Nova Scotia, and were designated SC. This reduced the HX convoys to a reasonable size of about 45 ships. The HX convoys sailed on a 4-day cycle, while the SC convoys were on an 8-day cycle. In December, Sydney was abandoned as a convoy assembly port, but the SC convoys were to continue to sail from Halifax.

In order to extend the antisubmarine escort further west, the convoy intervals were lengthened, with HX convoys sailing at alternate 6- and 4-day intervals, while the SC convoys sailed at 10-day intervals. In addition, Loch Ewe, in the northern part of Scotland, was started as an assembly port for ships on the east coast of England, and destroyers serving as antisubmarine escorts were able to refuel there and operate further west.

In February 1941, two HX convoys were routed on a southern course but heavy air attacks resulted in these convoys being rerouted to the north. Following an attack by a surface raider and the sighting of two German battle cruisers in the Atlantic, it was decided to give close battleship cover to all Halifax convoys. This threat of surface raiders also led to the discontinuance of the Bermuda section of HX convoys and ships were routed independently to the Halifax assembly.

British convoys were much harder hit during this second period than in the previous period. The number of ships convoyed monthly increased to about 3600, with 26 of these being sunk monthly by U-boats (13 in escorted convoys, 3 in unescorted convoys, and 10 stragglers). This meant that the total loss rate to U-boats was about 0.7 per cent, more than three times as high as in the earlier period.

Moreover, the HX and SC convoys sailing across the Atlantic to England were much harder hit than other convoys. Of the 360 ships sailing monthly in these convoys (only 10 per cent of the total convoyed shipping), about 14 ships were sunk monthly by U-boats (over 50 per cent of the total losses of convoyed shipping). The loss rate to U-boats on these vital convoys was about 4 per cent, more than five times as high as for all convoys.

Despite these high losses in convoys, the chances of being sunk by a U-boat were still higher for independently routed ships. Comparable figures are available for shipping passing through the Northwestern Approaches during the 6-month period from September 1940 through February 1941. About 80 per cent of the total losses to U-boats occurred in that area. Of the 1180 ships sailing through this area monthly in convoy, about 29 were sunk monthly by U-boats for a loss rate of about 2½ per cent. Of the 70 independently routed ships sailing through this area monthly, about three were sunk monthly by U-boats for a loss rate of about 4 per cent. In making this comparison, one should keep in mind that the ships sailing independently were generally capable of making a speed of at least 13 knots, much higher than the average speed which ships sailing in convoys were capable of making. This means that if all shipping had sailed independently the loss rate would probably have been much higher than the 4 per cent experienced by the select group of ships that sailed independently.

2.2.2 Aircraft

During the second period, increased use was being made of aircraft as a counter to U-boats. Though suffering from many limitations for antisubmarine operations, the airplane possesses obvious advantages denied to surface craft (*e.g.*, speed, cheapness, large field of vision, and economy of personnel and materiel). A U-boat on the surface can rely on the fact that she will almost certainly sight an enemy ship before she, herself, is seen. However, she must always keep a vigilant lookout against being surprised by a plane sweeping down out of the clouds.

In an attempt to improve the lethality of aircraft attacks, Coastal Command tried using naval depth charges modified for air use. Sunderland aircraft started carrying both depth charges and bombs in July 1940. The first success of this new weapon came on August 16 when a U-boat was severely damaged as a result of a depth-charge attack. The Sunderland plane, carrying two depth charges and four 250-pound antisubmarine bombs, first dropped a single depth charge set to explode at a depth of 100 feet about 20 yards ahead of the conning tower of the submerging U-boat. The U-boat was forced to the surface and two minutes later the second depth charge, set for 150 feet, was dropped about 20 feet

ahead of the conning tower. The U-boat was again blown to the surface and was then observed to sink sideways. On the third attack the stick of four bombs was dropped on the submerged U-boat. Air and oil came to the surface. In view of the initial successes of depth charges, steps were immediately taken to modify other Coastal Command aircraft in order to enable them also to carry depth charges. It was expected that the lethal value of aircraft attacks on U-boats would be considerably increased by this change.

The night attacks on convoys led, in September 1940, to the fitting of radar to the aircraft of Coastal Command and the Fleet Air Arm. This was supposed to be especially valuable for detecting U-boats on the surface at night and it was hoped that this would make it possible to operate aircraft at night for convoy escort work. It was also intended to provide the maximum air escort for the three hours before darkness falls, as this is the period in which U-boats could be found in shadowing positions preparatory to the night attack.

After the evasive routing of shipping had led to the start of wolf-pack tactics in February 1941, the shadowing U-boat became the main problem. Having contacted a convoy, the U-boat took great care not to reveal her presence by attacking in daylight, but shadowed the convoy at some distance. There was, therefore, only a small chance of the limited number of escorts discovering these U-boats and this task fell to the escorting aircraft. In view of this it was decided to reinforce the number of Coastal Command aircraft available for escort duty in the Northwestern Approaches. Consideration was also given to the problem of evolving the best type of aircraft patrol, round the convoy, to prevent the U-boat from shadowing it.

Despite the curtailment of routine antisubmarine patrols in favor of anti invasion patrols during this period, the average number of hours flown monthly by Coastal Command aircraft on antisubmarine duties increased by about 1000 hours over the previous period to reach 6300 hours, 5100 hours on convoy escort and 1200 hours on patrol. The number of flying hours on antisubmarine work dropped to about 4000 during the winter months of December 1940 and January 1941, due to longer hours of darkness and poorer weather. By March 1941 it was again up to about 8000 hours. This increased amount of flying was less productive than during the first period, as the number of sightings made monthly dropped to about 14 and the attacks to about 8. This decrease in the number of sightings, despite the increased number of U-boats at sea, was due mainly to the movement of the U-boats further westward, out of range of much of the flying. Again, about 10 per cent of the attacks resulted in some damage to the U-boat but the lethality of the attacks improved, as two (about 2½ per cent) of the attacks resulted in the probable sinking of a U-boat.

2.2.3 Scientific and Technical

Considerable research was done during this period on improving Asdic sets with one of the chief goals being the development of practical depth-determining gear. Very little progress was made on this difficult problem and the only immediate solution was the use of larger depth-charge patterns to counterbalance the large effect of the unknown factor of depth.

Another scientific development during this period was the extensive use of high frequency – direction finding [HF/DF] towards the end of 1940, after Germany had acquired the French bases and the U-boats had started widespread operations in the Atlantic. The principle of HF/DF was that a shore station could determine the bearing of any U-boat making a radio transmission, and it was hoped that the point of interception of the bearings from several shore stations would determine the transmitting U-boat's position. However, as more HF/DF shore stations became available around the Atlantic shores and as U-boats started to operate in numbers on the Atlantic trade routes, it became clear that shore-based HF/DF could only provide a rough indication of the general area in which the U-boat was and, at best, it could only provide a warning for a threatened convoy and so assist convoy routing. The Germans appreciated this and felt that shipborne direction-finding was restricted to medium frequencies. They therefore used high-frequency communications extensively once contact had been made with the convoy. As a result it was realized that HF/DF on convoy escorts themselves might do a great deal more; it might even enable the escorts to find U-boats before they could launch their attacks. The immediate requirement was an HF/DF outfit for ships which was quick and easy to operate.

However, the main scientific achievement during this period was the introduction of radar sets on

both ships and aircraft. Radar worked on the principle of transmitting short pulses of very high-frequency radio waves and then receiving the echoes from objects, like a U-boat on the surface. The echoes would enable the range and bearing of the object to be determined even at night and in conditions of poor visibility.

We have seen that the heavy shipping losses suffered at the start of this period as a result of night attacks on convoys had made radar an urgent necessity. As a stop gap, the first radar sets fitted in destroyers were of a Royal Air Force design known as air-surface vessel [ASV] or in the British Navy as radio direction-finding [RDF] Type 286 M. The fitting of these sets on ships was started about November 1940 and by April 1941 radar had been fitted on about 40 destroyers of the Western Approaches Command. It was hoped that radar would enable the escorts to detect the presence of any U-boat on the surface within a radius of some two or three miles.

Type 286 M had a fixed aerial and received echoes from a target over an arc covering about 50 degrees on each side of the bow and also over a similar arc astern at considerably shorter ranges (back echoes). The wavelength of these early sets was relatively long, over a meter, and consequently the aerial had to be very high above the surface of the sea before any considerable range could be obtained on small objects. This limited the effectiveness against U-boats of early radar sets on ships, but not on aircraft, as a plane flying at 2500 feet could expect to detect a U-boat on the surface at a range of about 15 miles.

Radar could be used in antisubmarine warfare for several subsidiary purposes, besides the main one of detecting U-boats. It could give warning of the approach of aircraft; it could be used in low visibility to make contact with single merchant ships or convoys; to pick up navigation buoys; to keep station on a convoy at night; or for making landfall.

By January 1941 it appeared that, as an antisubmarine device, radar on surface ships had been a disappointment. Escorts had considerable trouble owing to confusing "back echoes" from the convoy. As a temporary measure it was hoped to alleviate this trouble by reducing the range scale from ten miles to five miles. Work was also being done on a newly designed aerial, screened to cut out back echoes. At the end of this period, in March 1941, new types using shorter wavelengths and directional aerials were under trial and an improved radar set of naval design, Type 290, was in production and was to replace Type 286.

2.2.4 Sinking of U-boats

Surface craft continued to be the most effective craft in attacking and sinking U-boats during this period, making about 25 attacks a month. Of the 23 U-boats sunk or probably sunk in the Atlantic, surface craft could be credited with 13, or about 53 per cent. Submarines proved highly effective early in this period, patrolling close to the French bases, and torpedoing five U-boats in September 1940 and another in December. These submarine attacks made it necessary for the U-boats to enter and leave their bases submerged. Two U-boats were probably sunk as a result of aircraft attacks, one was sunk as a result of a combined attack by a ship and plane, and another was mined.

In addition, one German U-boat was known to have been sunk under unknown circumstances while 11 Italian U-boats were sunk in the Mediterranean, with surface craft again accounting for six, or 55 per cent of them. Italian U-boats operating outside the Atlantic had very little success against Allied shipping, as only five ships of 28,000 gross tons were sunk in the Mediterranean and Indian Oceans during the first two years of the war, from September 1939 to September 1941.

2.3 SURVEY OF RESULTS

2.3.1 From the U-boat's Point of View

The new U-boat tactics adopted during this second period had accomplished their primary objective of reducing the high rate of loss of U-boats. The average number of U-boats at sea in the Atlantic during this period rose to about 10, while only about 2½ of these were lost monthly. The average life of a U-boat at sea had increased by about 33 per cent, from 3 months to 4 months.

In addition, the efficiency of U-boats in sinking ships increased slightly, as the average U-boat sank four ships of about 22,000 gross tons per month at sea. The combined effect of these two factors improved the overall exchange rate to 16 ships of about 88,000 gross tons sunk for each U-boat sunk or probably sunk, an extremely profitable transaction for the U-boats.

From a quantitative point of view, the position of the German U-boats had improved considerably during this period as the increased U-boat building program, which the Germans had started shortly after England entered the war, began to take effect. As a result of commissioning about 45 new ocean-going U-boats while losing only about 18 of the large ones (500 tons or larger) Germany had about 51 ocean-going U-boats available at the end of this period, about twice as many as it had at the start of the period.

Thus the Germans would be able to send many more U-boats out to sea during the third period than they had sent during the early periods of the war. However, they had lost many of their ablest and most experienced captains and crews, and these were not as easily replaced as the U-boats themselves. The necessity of sending out relatively inexperienced U-boat captains was probably a factor influencing the Germans to decide, in February 1941, to operate their U-boats in groups, so that several inexperienced captains could operate together with a more experienced one.

2.3.2 From the Allies' Point of View

Total shipping losses of the Allied and neutral nations were about 456,000 gross tons a month during the second period, more than 60 per cent higher than during the first period. Meanwhile the building rate had increased only slightly to about 114,000 gross tons a month, making the net loss of shipping about 342,000 gross tons a month. Total shipping available had decreased from about 38,000,000 gross tons at the start of the second period to about 35,000,000 gross tons at the end of the second period.

Of the 456,000 gross tons of shipping lost monthly, about 404,000 gross tons were lost by enemy action. U-boats accounted for 42 ships of 224,000 gross tons a month (55 per cent of the total tonnage lost by enemy action), more than twice the monthly tonnage sunk by U-boats during the first period. Monthly shipping losses due to enemy surface craft jumped to 87,000 gross tons (22 per cent) and those due to enemy aircraft increased to 61,000 gross tons (15 per cent). Monthly losses due to mines dropped from second place in the first period to only 27,000 gross tons (7 per cent), with other and unknown causes accounting for the other 1 per cent of the total losses due to enemy action.

There is no doubt that the U-boats had inflicted a serious defeat on the Allies in the Battle of the Atlantic during the second period, but the situation was beginning to look more promising toward the end of this period. One favorable element was the increasing number of antisubmarine ships and aircraft becoming available for convoy escorts as the threat of the invasion of England was decreasing. The number of antisubmarine ships suitable for ocean escort (*i.e.*, destroyers and patrol craft such as sloops, frigates, corvettes) had increased from about 235 at the start of this period to about 375 (includes 240 destroyers) at the end of the period. Important factors in this increase were the coming into service of the new corvette and also the transfer of the 50 old Town class destroyers from the United States to England in September 1940. These destroyers were equipped with U. S. echo-ranging gear, called sonar, which was similar in principle to the British Asdic.

In addition, an increasing number of ships and planes were being equipped with radar in order to combat the U-boat's night activity. Officers and crews had increased experience and training in antisubmarine warfare and had shown in March 1941 that they could inflict heavy losses on U-boats attacking adequately escorted convoys. It appeared as if the main problem during the third period would be that of meeting the westward movement of the U-boats by extending antisubmarine escort westward, without weakening the escort strength.

Chapter 3

THIRD PERIOD

START OF WOLF PACKS; END-TO-END ESCORT OF CONVOYS

APRIL 1941–DECEMBER 1941

3.1 U-BOAT OFFENSIVE

The fruits of the intensified German U-boat construction program, started late in 1939, were beginning to appear as the average number of U-boats at sea in the Atlantic steadily increased from about 18 in April 1941 to about 36 in August 1941. The main features of U-boat tactics during this third period were the increasing use of wolf-pack attacks forced upon the Germans by the evasive routing of British convoys and the scarcity of experienced U-boat commanders.

The outstanding successes achieved by escorts in the Northwestern Approaches during March 1941 produced the direct result that, in April, U-boats abandoned the method of close attack on the surface while antisubmarine escorts were in company. The U-boats continued their search for weak spots in the antisubmarine defenses by moving away from the vicinity of England, where air coverage was heavy, and extended their operations further westward where they could attack convoys before the antisubmarine escort had joined. There was also a southward movement of the U-boats with increased activity in the Azores and Freetown Areas.

April opened somewhat disastrously with heavy attacks, started before the antisubmarine escort had joined, on Convoy SC 26. About five U-boats participated in these attacks, ten ships were sunk, and, in addition, the armed merchant cruiser ocean escort was damaged by a torpedo hit. One of the attacking U-boats was sunk after the antisubmarine escorts had joined. Towards the end of April, four ships were sunk from Convoy HX 121 as a result of the first submerged daylight attack by a pack of U-boats. The shipping losses to U-boats in April were about the same as in March, with 41 ships of 240,000 gross tons sunk. However, only about 30 per cent of the tonnage sunk by U-boats was in convoy in April as compared with 60 per cent in March. About 13 per cent of the tonnage sunk by U-boats in April was sunk in the Azores Area and another 15 per cent in the Freetown Area.

The total shipping losses, from all causes, amounted to 682,000 gross tons in April 1941, a higher figure than for any previous month in the war. This was due mainly to the heavy shipping losses to enemy aircraft, about 296,000 gross tons, most of these losses occurring in the Mediterranean in connection with the evacuation from Greece and Crete.

As a result of the heavy attack on Convoy SC 26 at about 28° west longitude, the Iceland routing scheme was adopted earlier than was originally intended. Escorts were based on Iceland, making it possible to meet convoys where the escort from England had to leave, and then to escort the convoys out to about 35° west longitude, the escort there picking up an incoming convoy and then turning it over to an escort group from England. Sunderland and Hudson aircraft were also moved to Iceland to provide air coverage for convoys in waters which could not be covered by aircraft based on England.

Obviously this considerable increase in the distance over which transatlantic convoys were escorted was only achieved at the expense of weaker individual escorts with each convoy. This was partly compensated by reinforcing the Western Approaches with Asdic-fitted minesweepers. It is equally clear that the use of Iceland necessitated a certain rigidity of routing and tended to make the location of convoys by U-boats and enemy aircraft a simpler business. Against this, the daylight hours in these northern latitudes were rapidly lengthening as the summer months approached and the U-boat danger in daylight was a lesser menace than at night.

The upward trend in shipping losses to U-boats continued as 58 ships of 325,000 gross tons were sunk in May. Over half the losses occurred in the Freetown Area, where a group of about six U-boats sank 32 ships of 186,000 gross tons during the month. To meet the increased U-boat activity in that area, additional escorts were added to the Freetown forces and

action was taken to divert all shipping from the Freetown Area, except those ships which must of necessity pass through those waters.

Attacks on independents continued to increase as only about 20 per cent of the shipping sunk by U-boats in May was in convoy. In addition, the U-boats continued to move further westward and on May 20 located Convoy HX 126 at about 41° west longitude, before the antisubmarine escorts had joined. Eight ships were sunk before the convoy was forced to disperse. This attack forced the adoption of complete transatlantic escort.

It was felt that the considerable weakening in the number of escorts with a convoy must be accepted in order to provide some degree of protection throughout the voyage. Complete transatlantic escort was accomplished by basing escort forces in St. John's, Newfoundland, and escorting in stages from England, using Iceland as a refueling base. The Royal Canadian Navy cooperated in these measures by placing all available destroyers and corvettes at the service of the Newfoundland Escort Force. Canada had about 35 ships fitted for antisubmarine service at that time. The first escorts from St. John's sailed on May 31, 1941, and, as a natural sequence to this development, it was decided by the middle of June to escort the convoys all the way from Halifax. The long endurance corvettes were to run all the way between Halifax and Iceland, with the destroyers being limited to St. John's.

Areas of U-boat activity in June were farther afield and wider spread than before, with reports of U-boats near Newfoundland and south of Greenland. Despite the magnitude of the effort exerted, the shipping losses showed an improvement over May, with 57 ships of 296,000 gross tons being sunk by U-boats in June. Despite the increasing number of U-boats at sea, the losses were kept down by the efficiency of British countermeasures as five U-boats were sunk during June by surface craft. Losses in the Freetown Area were greatly reduced and the U-boats had difficulty in locating the transatlantic convoys.

When they did finally locate Convoy HX 133 on June 23, the results must have been rather disappointing to the Germans, as only five ships were sunk at the cost of at least two U-boats sunk. This successful defense of this convoy was due in large measure to the fact that, when DF bearings indicated that HX 133 had been sighted by a U-boat, the escort was increased from one destroyer and three corvettes to two destroyers, one sloop, and ten corvettes. This was accomplished by taking the risk of stripping the escorts from two OB convoys within comparatively easy reach. Fortunately, one of these OB convoys escaped unscathed while the other suffered the loss of only one ship.

On June 22, 1941, Germany invaded Russia and this seemed to end the threat of invasion of England for the time being. This released additional air and surface craft to help in the battle against the U-boats. In addition, German aircraft were diverted to the Eastern Front and attacks on shipping by aircraft were greatly reduced during the last half of 1941.

The average number of U-boats at sea continued to increase during July and August, but they had very little success as only about 23 ships of 90,000 gross tons were sunk in each of these months. This meant that the average U-boat at sea in the Atlantic was sinking less than one ship a month, a much lower rate than had been experienced in the past. In an endeavor to make the interception of shipping easier the U-boats withdrew to the eastward towards the end of July and concentrated in the waters west of Ireland and to the east of 25° west longitude. This placed them at a focal point of shipping where they could intercept both the East-West and the North-South convoys. However, the U-boats had no better luck there in August than they had in July. By this time, even the Gibraltar and Freetown convoys had more or less complete end-to-end escort. Towards the end of August, there were indications that the U-boats were resorting to long-range attacks on convoys, probably firing a browning salvo, and also to deliberate attacks on escorts. This policy of attacking escorts might have proved more profitable in the earlier days of the war, when the number of escorts with convoys was much smaller and when the general escort situation was much tighter.

In addition to the defensive successes scored in August, this month was marked by one of the outstanding events of the U-boat war, the surrender of U-570 to a Hudson aircraft on August 27, 1941. U-570 left on her first cruise on August 24 and was at sea for only 71 hours before she surrendered. The U-boat came to the surface at 1030 on the 27th, the precise moment the Hudson from Squadron 269 was overhead. The U-boat tried to crash dive but the Hudson was too quick for her, diving from 500 feet to 100 feet, and dropping four depth charges. Captain Rahmlow, believing the U-boat more seriously dam-

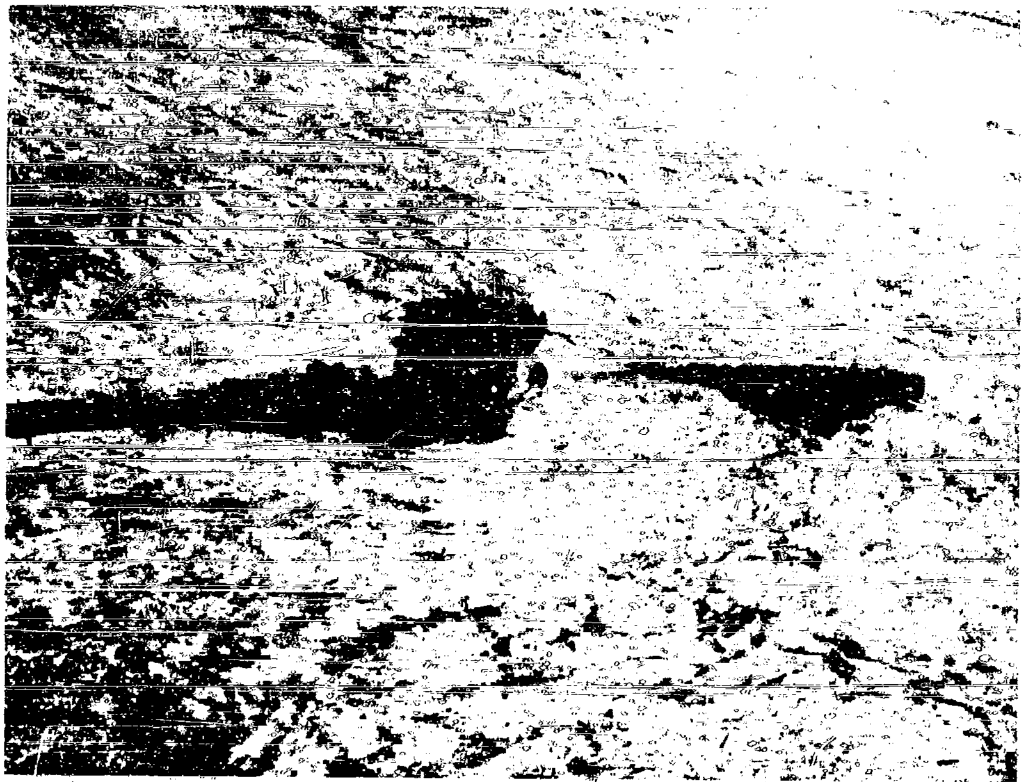


FIGURE 4. Surrender of U-570 (HMS *Graph*) to Hudson aircraft S 269 on August 27, 1941. Note German crew crowded into conning tower.

aged than was actually the case, ordered the crew to put on life jackets and go to the conning tower. The Hudson opened fire and kept the crew from abandoning the U-boat. After a white flag was displayed by the U-boat the Hudson guarded it until relieved by a Catalina. A trawler arrived at 2250 and U-570 was towed to Iceland. She was subsequently repaired and re-christened HMS *Graph*, proving an invaluable addition to the British Navy. This was the first U-boat actually captured by the British and proved to be an extremely valuable source of information about the operating characteristics of U-boats.

U-boat activity continued at a high level in September and their intensive efforts met with greater success than during the previous two months. Allied shipping losses rose sharply to 51 ships of 205,000 gross tons sunk by U-boats, with 70 per cent of the tonnage sunk being in convoy. This increase was due in a large measure to the severe casualties suffered by four large convoys as a result of determined and sustained attacks by wolf packs. Two of these convoys were slow SC convoys which were intercepted and heavily attacked south of Greenland, losing 21 ships and one escort. Two U-boats were sunk by escorts during these attacks. The other two convoys, homeward bound from Freetown and Gibraltar, lost 15 ships and one escort to the U-boats.

However, in viewing the situation at this time it would be well to compare it with the previous year. In September 1940, when about seven U-boats were at sea, the losses to U-boats were about 300,000 gross tons. In September 1941, when there were about 35 U-boats at sea, the losses to U-boats were only about 200,000 gross tons. In September 1940 the U-boats were attacking convoys with impunity. Rarely was a U-boat sighted during her attack, and even more rarely was she counterattacked. In contrast to this, in September 1941 it was a matter of the keenest disap-

pointment if a convoy were attacked and the enemy escaped unpunished. The limited number of escorts, usually about one destroyer and three or four corvettes, although unable to prevent the U-boats from attacking the convoy, were generally able, with the help of covering aircraft, to shake off the pursuing U-boats by persistent counterattacks. No convoy was attacked for more than three successive nights in September 1941.

The effect of Coastal Command aircraft on U-boat operations may be seen by the fact that, of the tonnage sunk in the North Atlantic during September by U-boats, about 75 per cent was lost in the area outside the economical range of Whitley and Wellington aircraft (400 miles). Aircraft made 45 sightings and 39 attacks on U-boats in September, the highest monthly figures recorded to that date. September was also marked by the introduction of HMS *Audacity*, an auxiliary aircraft carrier, as a convoy escort. One of her fighter aircraft shot down a Focke-Wulf attacking the rescue ship of Convoy OG 74.

As the radius of U-boat operations in the Atlantic extended further west and U. S. ships were being sunk by U-boats, the U. S. Navy announced on September 15, 1941, that it would provide protection for ships of every flag carrying land-aid supplies between the American continent and the waters adjacent to Iceland, on which a U. S. base had been established in July 1941. On September 16 the first convoy (HX 150) to have U. S. Navy ships as part of its escort sailed from Halifax.

The losses in October 1941 dropped to 32 ships of 157,000 gross tons sunk by U-boats. Only one convoy (SC 48) was heavily attacked by U-boats; nine ships and two escorts were sunk and the USS *Kearny* was torpedoed but arrived at Iceland. The USS *Reuben James* was sunk by a U-boat torpedo on October 31 while acting as an escort of Convoy HX 156. In a number of other cases the convoys were located by U-boats but the escorts were able to drive them off without suffering serious losses.

An interesting feature of the operations during October was the disinclination of the U-boats to pursue their quarry too far northward or eastward, presumably because they did not care to enter the areas swept by Coastal Command aircraft. This is indicated by the fact that of the 26 ships sunk within 800 miles from air bases, 14 were lost in portions more than 600 miles out and 12 in the 400- to 600-mile zone (covered lightly by Catalinas). No ships were sunk within 400 miles from Coastal Command bases. This meant that the U-boats were being forced ever further westward, with consequent greater wastage of time and U-boats, particularly in winter. In addition, air attacks on transit U-boats in the Bay of Biscay began to increase in frequency and effectiveness, thereby further cutting down the operational time of U-boats.

During the first week of November, the scale of the U-boat effort was probably the greatest and the scope of their patrol the widest spread of the whole Atlantic campaign up to that time. When Convoy SC 52 was intercepted shortly after rounding Newfoundland and four ships were sunk on November 3, it was considered prudent not to risk it upon a transocean journey for the greater part of which many U-boats might have maintained continuous harrying attacks. The convoy put back to port and the ships sailed later in Convoy SC 54, which consisted of 71 ships. This decision proved fortunate, as there followed a period of successful evasion which lasted for the remainder of the month. The total losses for November 1941 dropped to 12 ships of 62,000 gross tons, the lowest figure since May 1940. Weather contributed to the reduction in shipping losses but the main factor was skillful evasive routing. Successful evasion meant fewer chances of contacts between escorts and U-boats and therefore less chance for the destruction of U-boats.

In the meantime the British offensive in Libya had been launched and the Germans withdrew a large proportion of their U-boats from the Atlantic to the Mediterranean to help the Italian Fleet and temporarily, at least, to use their U-boats for the transport of military supplies to Rommel. Toward the end of November, convoys from Gibraltar were suspended and every available ship was used in an endeavor to close the Straits of Gibraltar to the passage of U-boats and to destroy U-boats attempting passage. Two German U-boats attempting the passage were sunk during the month, one by surface craft and the other by a Dutch submarine.

The perceptible slackening in tension in the North Atlantic that started toward the end of November continued throughout December 1941. The losses in the Atlantic continued at a very low level, with only 10 ships of about 50,000 gross tons sunk by U-boats during the month. However, the tendency of the U-boat war to become world wide became apparent,

as for the first time the losses to U-boats outside the Atlantic became significant. Seven ships of 27,000 gross tons were sunk by U-boats in the Mediterranean, three in the eastern approaches to Gibraltar and four while on passage between Alexandria and Tobruk. However, the enemy paid a heavy price for these seven ships, as five U-boats were sunk in the Mediterranean during December.

Japanese submarines sank nine ships of 42,000 gross tons in the Pacific during the remainder of December after their attack on Pearl Harbor on December 7, 1941. One Japanese submarine was probably sunk. Over 200,000 gross tons of shipping were lost in the Pacific due to capture by the Japanese or unknown causes. Accordingly, the total shipping losses for the month (from all causes) rose to over 500,000 gross tons.

The outstanding feature of the month's operations in the Atlantic was the prolonged engagement between Convoy HG 76 and a pack of half a dozen U-boats. The escorts sank four U-boats (including U-567, commanded by Endrass, one of the leading U-boat aces) and only two of the merchant ships of the convoy were lost. However, one escort and HMS *Audacity*, an auxiliary aircraft carrier, were also sunk by the U-boats. As 1941 drew to an end, the number of U-boats in the Atlantic began to rise again, the majority leading westward.

3.2 COUNTERMEASURES TO THE U-BOAT

3.2.1 Convoys

U-boat activity during the early months of this period forced the adoption of complete end-to-end escort of British convoys. Thanks to the steadily increasing number of escorts becoming available, and to cooperation from the Canadian and United States Navies, this did not result in the anticipated serious weakening in the protection of the convoys. In fact, ships sailing in convoy were safer in this period than they had been in the preceding period, as of the 4100 ships being convoyed monthly only 14 (about 1/3 of 1 per cent) were sunk monthly by U-boats. By the end of 1941, it appeared, as evidenced by the battle of Convoy HG 76, that the wolf-pack attacks on convoys could be beaten off without serious losses to the convoy and in turn these attacks could prove costly to the U-boats, provided a sufficient number of escorts were present.

An analysis of 17 of the convoys attacked by the U-boats at about this time gives us some information about the "average attacked convoy." This convoy was engaged by 4.2 U-boats, of which 2.6 succeeded in delivering effective attacks. A total of 4.6 ships in the convoy were torpedoed, 1.7 ships being torpedoed in each effective attack. Of the 4.2 U-boats engaging the convoy 3.2 (or 76 per cent) were attacked by the air and surface escorts and 0.65 (or 15 per cent) of them sunk.

There were not many changes made in the convoy system during this period. The minimum speed for HX convoys was raised from 9 knots to 10 knots, with the minimum speed for SC convoys remaining at 7½ knots. In July 1941 a rule was introduced requiring ships of less than 15 knots, crossing the Atlantic, to sail in convoy. The designation of the OB convoys (outward-bound from England) was changed to ON for the north-bound convoy heading for Halifax and to OS for the south-bound convoys heading for Freetown. July 1941 also marked the introduction of CAM ships in convoy. These were merchant ships equipped with a catapult-launched fighter aircraft which was to be used against enemy reconnaissance aircraft. In August 1941, the first convoy to Russia sailed for Archangel. No losses were suffered on the convoys sailing between England and Russia during 1941.

3.2.2 Aircraft

At the beginning of this period, in April 1941, it was apparent that an improvement in the quality of aircraft attacks was urgently needed. Actual kills by aircraft had been disappointingly few and it was felt that, on the relatively rare occasions when a pilot sights a U-boat, he should have a reasonably good chance of bringing off a kill. A committee of Coastal Command scientists and naval representatives was therefore formed to review this situation.

Analysis showed that in 35 per cent of the aircraft attacks the U-boat was still visible at the time of release of the depth charges and that in 15 per cent of the attacks the U-boat had disappeared less than 30 seconds previously. The solution adopted was to concentrate on those U-boats which were still on or near the surface and to adjust tactics, depth-bomb settings and spacing, so as to give the aircraft the maximum chance of killing in these conditions, since the probability of hitting the U-boat under these conditions is much greater than it is after the U-boat has been submerged for some time.

Instructions were accordingly issued by Coastal Command in June 1941 providing that the depth setting for all depth charges should be 50 feet, the spacing between charges should be 60 feet, and all depth charges were to be released in one stick. The need for more frequent practice and training was also stressed and a standard for bombing accuracy was set up requiring a mean radial error of all bombs dropped of not more than 20 yards.

This change resulted in a significant improvement in the quality of aircraft attacks on U-boats. Aircraft made about 27 sightings a month during this period and about 18 of these resulted in attacks on U-boats. The proportion of these attacks which resulted in at least some damage to the U-boat rose from about 10 per cent in the earlier periods to about 25 per cent in this period. The lethality of the aircraft attacks did not change much, as only about 2½ per cent of the attacks resulted in the U-boat' being sunk. However, it was realized at the end of this period that even the 50-foot depth setting was too deep for surfaced U-boats and steps were being taken to modify depth charges to allow a 25-foot depth setting.

As the U-boats moved further westward, the total number of flying hours by Coastal Command aircraft on antisubmarine duties decreased, but transit U-boats crossing the Bay of Biscay on their way to and from French bases began to receive more attention. In the period September to November 1941, 36 attacks were made on U-boats in this area. This was equivalent to each U-boat's being attacked in the Bay on one out of every three cruises and was a sufficient menace to force them to remain submerged in the Bay during the daytime in December, thereby increasing their transit time. By December 1941, Coastal Command had initiated night antisubmarine patrols with radar-fitted aircraft in the Bay of Biscay.

Midway in 1941, the British scraped together a squadron of long-range planes, new untried Liberators rejected by U. S. Air Forces. Fitted with Mark II radar, they did a dual job, ranging far out on patrol and giving air cover to convoys asking for help.

The flying effort during this period was marked by the increased use of protective sweeps around convoys to put down shadowing U-boats, as distinct from the close convoy coverage provided earlier. It was also marked by the first attempt, in May 1941, by radar-equipped aircraft to hunt a U-boat to exhaustion. Although this attempt did not succeed, much useful information was obtained from this operation.

3.2.3 Scientific and Technical

A new antisubmarine weapon for use by surface craft was coming into production at the end of 1941. This weapon was "Hedgehog," a multispigot mortar which throws 24 projectiles fitted with contact fuzes so as to produce a pattern in the form of a ring whose center is about 250 yards ahead of the ship. The Hedgehog pattern, theoretically, has a greater chance of killing a submarine than the depth-charge pattern due to the fact that its design incorporates the following three important principles:

1. *Ahead thrown.* This permits a reduction in blind time from 45–90 seconds to 15–20 seconds.

2. *Multiple small charge.* Three hundred pounds of high explosive (lethal range of 21 feet) has about one half the chance of killing the U-boat as ten 30-lb charges (lethal radius of 6 feet). The lower limit of the charge is the smallest weight which will have a reasonable chance of sinking the U-boat when it explodes on the target.

3. *Contact firing.* The contact fuze "sweeps" all depths. This is of particular importance in view of the fact that the antisubmarine gear used at that time did not determine the depth of the U-boat.

However, against these advantages of Hedgehog must be considered the fact that the large explosion of depth charges has a desirable anti-morale effect and produces considerable shaking up of the U-boat in cases where the depth charges are not lethal. Hedgehog fails to do this since the charges explode only on hitting the U-boat.

During this period, the results from radar were more promising as a consequence of increased training and knowledge of the gear. A new set, Type 271, was being fitted on British corvettes. This was a short-wave (10 cm) "beam" principle set and constituted a great advance in radar for antisubmarine purposes. The average range at which radar contact was made on a U-boat during this period was about 4000 yards, with the maximum range being 7000 yards.

Coastal Command was also experimenting, during this period, with a searchlight, carried in a Wellington aircraft, to provide illumination for night attacks on U-boats.

3.2.4 Sinkings of U-boats

The steadily upward trend in the number of U-boats sunk or probably sunk monthly continued throughout this period, reaching a new high for the

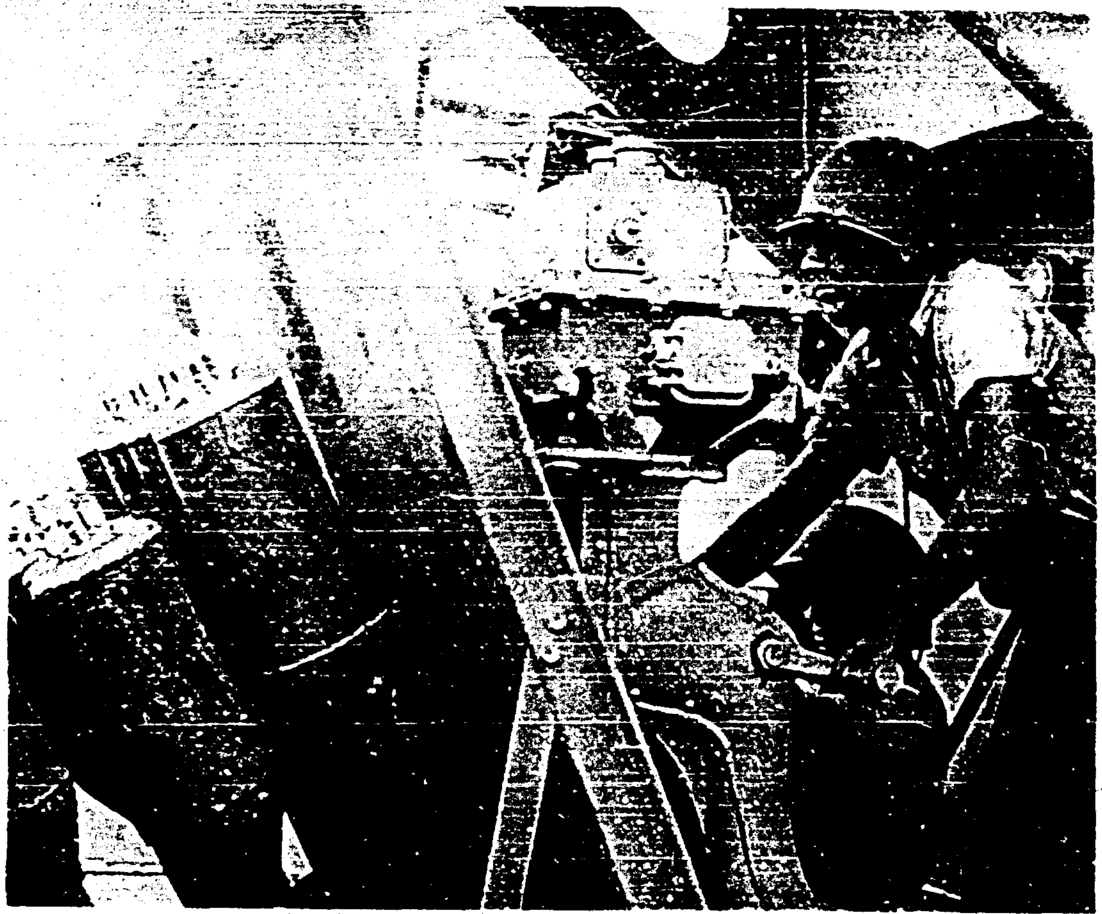


Figure 2. Hedgehog ready to fire.

war in December 1941 when 13 U-boats are believed to have been lost. However, it should be kept in mind that the rate of increase in the number of U-boats sunk was much lower than the rate of increase in the number of U-boats at sea, so that the average U-boat at sea had a much smaller probability of being sunk in this period than in either of the two preceding periods.

The total number of enemy U-boats sunk during this 9-month period was 44. Thirty of these were lost in the Atlantic (22 German and 8 Italian) and 13 in the Mediterranean (6 German and 7 Italian). One Japanese U-boat was probably sunk in the Pacific during December. Two German U-boats were known to have been lost in the Baltic as a result of collisions with their own craft.

Surface craft continued to be the most effective craft in sinking U-boats, accounting for 20 of the 30 U-boats sunk in the Atlantic. Another two were sunk as a result of combined attacks by ships and aircraft. Two were lost as a result of aircraft attacks and one was torpedoed by a submarine. The circumstances under which the other five U-boats, known to have been lost in the Atlantic, were sunk are not known.

During the last six months of 1941, one out of every three U-boats attacked by surface craft was at least damaged, while one out of every seven attacked was sunk or probably sunk.

3.3 SURVEY OF RESULTS

3.3.1 From the U-boat's Point of View

The average number of U-boats at sea in the Atlantic during the third period was about 30, three times as many as in the previous period. Their main effort was directed in the form of wolf pack attacks against the North Atlantic convoys. They did succeed in forcing the Allies to adopt complete end-to-end

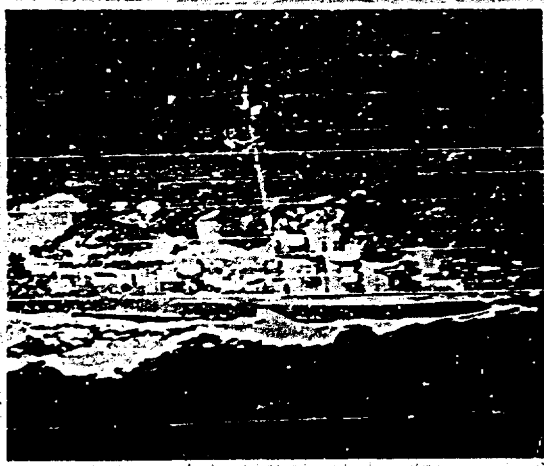


FIGURE 3. DE firing Hedgehogs on shakedown cruise. Projectiles can be seen above the bow.

escort of their transatlantic convoys but they definitely failed in their main objective of cutting off supplies to England and toward the end of this period there were signs of their shifting to other areas.

Despite this threefold increase in the average number at sea, the U-boats were able to sink only about 34 ships of about 166,000 gross tons monthly in the Atlantic during this period, or about 25 per cent less than in the previous period. This meant that the average U-boat was only sinking a little over one ship of about 5500 gross tons per month at sea, and was therefore only about one-fourth as effective as in the previous period. This drop in efficiency reflects the successful evasive routing of convoys and the very rapid expansion in U-boat personnel. This latter condition resulted in a high proportion of U-boats being sunk on their first cruise. The evasive routing of convoys also resulted in fewer contacts between convoy escorts and U-boats and consequently the average U-boat was relatively much safer during the third period. About 3½ U-boats were sunk monthly in the Atlantic, of the 30 at sea on the average, and consequently the average life of a U-boat at sea was about 9 months, more than twice as long as it had been in the previous period. The average U-boat during this period was sinking ten ships of about 50,000 gross tons before it was sunk itself. Hence, despite the longer lifetime of the average U-boat, the exchange rate was about 40 per cent less than in the previous period, reflecting the decreased effectiveness of U-boats in sinking ships.

The number of ocean-going German U-boats in commission was expanding at a very rapid rate, increasing from about 54 at the beginning of this period to about 200 at the end of 1941. About 174 German U-boats were commissioned during this period while only about 28 were lost. From the point of view of number alone, the U-boats offered a considerable threat and it seemed likely that with increased experiences the effectiveness of these new U-boats would increase.

3.3.2 From the Allies' Point of View

Total shipping losses of the Allied and neutral nations decreased to 363,000 gross tons monthly during the third period, while the building rate of new shipping increased to about 175,000 gross tons monthly. Consequently, the net monthly loss of shipping was only 188,000 gross tons, about 15 per cent less than during the preceding period.

Of the 363,000 gross tons of shipping lost monthly, about 325,000 gross tons were lost by enemy action. U-boats accounted for 175,000 gross tons a month, 54 per cent of the total lost by enemy action. Monthly losses to enemy aircraft increased to 75,000 gross tons, while the losses to enemy surface craft dropped to only 17,000 gross tons. Mines were responsible for only 19,000 gross tons a month, while other and unknown causes accounted for 37,000 gross tons a month.

The total shipping available decreased from about 35,000,000 gross tons at the beginning of this period to about 33,306,000 at the end of 1941, but the upward trend in shipping losses seemed to have been checked. The number of British antisubmarine ships suitable for ocean escort had increased from about 375 at the start of the period to about 500 at the end of 1941. In addition, the entry of the United States into the war added about 175 destroyers to the above numbers, but many of them were committed to action in the Pacific.

From the defensive point of view the U-boats, which constituted the main threat to Allied shipping, seemed to have been defeated in the Battle of the Atlantic during this third period. They were experiencing difficulty in locating Allied convoys and even when they did locate a convoy, the escorts were generally able to beat off the wolf-pack attacks without serious losses. Shipping losses to U-boats had been kept to a reasonable level, considering the number of

U-boats at sea, while shipping construction was gradually increasing. However, from an offensive point of view, the U-boats were still relatively safe. Surface craft acting as convoy escorts were the only serious threat to the U-boat, although aircraft were gradually becoming more effective in harassing and damaging U-boats. It seems, therefore, that the general situation in the Battle of the Atlantic at the end of 1941 was roughly the same as the situation which prevailed at the end of World War I—that is, with shipping losses checked, but with the U-boats relatively safe at sea.

Chapter 4

FOURTH PERIOD

HEAVY SINKINGS ON EAST COAST OF UNITED STATES

JANUARY 1942–SEPTEMBER 1942

41 U-BOAT OFFENSIVE

THE GERMANS started this period with about 200 ocean-going U-boats and new U-boats were being commissioned at the rate of about 20 a month. Admiral Doenitz was therefore able to maintain a large-scale U-boat offensive over widely spread areas throughout this period. The average number of U-boats at sea in the Atlantic increased steadily from 22 in January 1942 to 95 in September 1942. In addition, there were about 20 U-boats in the Mediterranean and about 20 available for operations in the Barents Sea. These U-boats were used in a specific effort to cut supply lines to Allied forces in Libya and Russia. Japan, at the start of this period, had about 75 U-boats which operated in the Pacific and Indian Oceans.

Despite this widespread U-boat activity, the main battle continued to be fought in the Atlantic Ocean. There, during the previous period, U-boat operations against escorted shipping had been steadily becoming less and less profitable. The average yield had been reduced to about one ship sunk per U-boat month at sea during the last period. The operation against Convoy HG 76 in December 1941 had been particularly costly, as only two merchant ships were sunk as against four U-boats sunk. It was natural, therefore, after the entry of the U. S. into the war, that the U-boats, continuing their search for weak spots in the Allied defenses, headed westward for the American coast in January 1942.

The U-boats, working their way down the American coastline from the Newfoundland banks, found exactly the weak spot they were looking for. The demands of the war in the Pacific and commitments in transatlantic escort (including destroyers transferred to the British in 1940) contributed to the United States' lack of preparedness for the scale of attack launched by the U-boats on the Atlantic coast in 1942. The forces available to combat these enemy activities were relatively untrained and inexperienced. With the limited number of antisubmarine craft, both surface and air, at their disposal, the U. S. Navy was unable to start convoying coastal shipping immediately, but tried during the early months of 1942 to cover the long coastal route by patrol. This produced a number of attacks on U-boats but it failed to prevent extremely heavy losses of shipping sailing unescorted along the coast.

U-boat activity in the West Atlantic began on January 12, 1942, when the first sinking west of 60° west longitude occurred. A force of about 20 U-boats began to operate off the Atlantic seaboard of the United States and in the coastal area of Nova Scotia and Newfoundland. These U-boats were rather selective in their choice of targets, preferring tankers and larger cargo ships and avoiding convoys. As long as worth while targets abounded in the form of unarmed and unescorted ships, the U-boats kept clear of escorts as even minor damage might well have prevented their return to distant bases.

The U-boats inflicted their heaviest losses in January in the Eastern Sea Frontier, sinking 14 ships of about 100,000 gross tons with a large proportion of the losses occurring at focal points of shipping such as Cape Hatteras, North Carolina, and Hampton Roads, Virginia. About 50,000 gross tons of shipping were sunk by U-boats in each of the Northwest Atlantic, Canadian Coastal, and Bermuda Areas. There was comparatively little activity in the remainder of the Atlantic, but Japanese U-boats sank 50,000 gross tons of shipping in the Pacific and Indian Oceans. The total losses for the month, 64 ships of 324,000 gross tons sunk by U-boats, were higher than those in any month in the previous period.

The situation became much worse in February 1942 with the world-wide shipping losses to U-boats reaching a new high for the war as 82 ships of 470,000 gross tons were sunk. About 90 per cent of these losses occurred in the U. S. Strategic Area as the number of U-boats operating in the West Atlantic increased and U-boat activity spread further south with ships being sunk off the coast of Florida and in the Caribbean Sea. Tanker losses continued to be severe, with the

tanker traffic to and from the West Indian and Venezuelan oil fields being an obvious objective of the U-boats. This was shown by an attack carried out by several U-boats on February 16 on six tankers off Aruba and in the Gulf of Venezuela, five being sunk and one seriously damaged.

During March the U-boats continued the same tactics with increased success as they sunk 94 ships of 532,000 gross tons. The Eastern Sea Frontier continued to be the most active area, with over 150,000 gross tons of shipping sunk there by U-boats. Possibly by way of diversion, a group of U-boats operated in the Freetown Area, sinking over 50,000 gross tons there.

The one encouraging feature of the month's operations was the first successful attacks on U-boats in the U. S. Strategic Area. Two U-boats were sunk in March as a result of attacks by U. S. Navy aircraft in the Canadian Coastal Zone. On April 15, USS *Roper* sank U-85 off Cape Hatteras, picking up 29 bodies, for the first confirmed sinking of a U-boat off the U. S. coast. The number of attacks on U-boats in the U. S. Strategic Area had increased from about 15 in January to about 60 in April.

These more effective countermeasures probably played some part in causing a small decrease in shipping losses in April, but a more important factor was the temporary suspension of sailings in certain areas. U-boat activity spread to the Brazilian Area during April as three ships were sunk off the north coast of Brazil, probably by Italian U-boats.

In the middle of May 1942, the U. S. Navy was able to start convoying shipping along the east coast. The effect of the institution of these convoys was immediately apparent. The U-boats avoided escorted shipping and the tonnage sunk by U-boats in the Eastern Sea Frontier in May dropped to 23,000 gross tons. Logically enough, the U-boats sought out the remaining soft spots, where unescorted traffic had to pass through focal areas, and operated actively off the mouth of the Mississippi and in the Yucatan Channel between Cuba and Nicaragua.

Although the average number of U-boats at sea in the Gulf Sea Frontier in May 1942 was only about four, these U-boats sank 41 ships of 220,000 gross tons there during the month, an all time high for sinkings by U-boats in any area. The average number of ships at sea in the Gulf Sea Frontier was about 75, so the average life of a ship at sea at that time was less than two months at that rate of sinkings.

Sinkings in the Caribbean Sea Frontier also increased, reaching about 170,000 gross tons in May. Consequently, despite the decrease in the Eastern Sea Frontier, the losses in the U. S. Strategic Area reached a peak of 116 ships of 567,000 gross tons sunk by U-boats in May. The world-wide shipping losses to U-boats also reached a new high for the war as 124 ships of 601,000 gross tons were sunk during this month. The number of attacks on U-boats in the Western Atlantic showed a promising increase, however, and two U-boats were sunk by U. S. Coast Guard cutters, one in the Eastern Sea Frontier and one in the Gulf Sea Frontier.

The world-wide shipping losses to U-boats reached their highest point in the war in June 1942, when 141 ships of 707,000 gross tons were sunk. The bulk of the increase over the figures for May was accounted for by increased activity by Japanese U-boats, which sank 70,000 gross tons in the Indian Ocean, mostly in the Mozambique Channel. The shipping losses in the U. S. Strategic Area were about the same as in May, falling off in the Gulf Sea Frontier but continuing to increase in the Caribbean and Panama Sea Frontiers. Mines were laid in the Chesapeake, causing several casualties in June. This mine-laying may have represented the first effort of one of the 1600-ton mine-laying U-boats introduced by Germany at about that time. Over 100 attacks were made on U-boats in the U. S. Strategic Area in June; three of these attacks resulting in sinking U-boats.

During July 1942 the convoy system on the east coast of the U. S. was greatly extended, with the bulk of shipping traveling in convoy. This increase in the number of convoys and an improvement in the strength of escorts were probably mainly responsible for the general reduction in sinkings of shipping throughout the U. S. Strategic Area. Only 230,000 gross tons of shipping were sunk by U-boats in the U. S. Strategic Area in July, less than half the amount sunk in June; this, despite the fact that the average number of U-boats at sea in the U. S. Strategic Area in July was about 15, higher than in any previous month. Increased aircraft patrols and better cooperation between surface and air units also contributed materially to this reduction of U-boat effectiveness in the West Atlantic. Another significant factor was the increase in the number of U. S. craft available for antisubmarine warfare: 134 ships in July as compared to 68 in April and 580 planes in July as compared to 350 planes in April. The increased effec-

tiveness of U. S. countermeasures is also illustrated by the fact that the number of U-boats lost in the U. S. Strategic Area reached a new high in July as seven were sunk, two in Eastern Sea Frontier, one in Gulf Sea Frontier, two in Panama Sea Frontier, and two in the Northwest Atlantic Area.

As a result of the greatly reduced losses in the West Atlantic, the world-wide shipping losses to U-boats dropped to 94 ships of 472,000 gross tons in July 1942. However, increased losses were suffered in the Freetown and Azores Areas with over 50,000 gross tons sunk by U-boats in each of these areas. Heavy losses were also suffered in July in the Barents Sea Area, where ten ships of 62,000 gross tons were sunk by U-boats from Convoy PQ 17 heading for Russia. In addition, 13 ships were sunk from this convoy by enemy aircraft. The convoy had been ordered to scatter when southeast of Spitzbergen to reduce losses from the enemy surface craft attack then apparently pending.

The shipping losses to U-boats increased slightly in August to 108 ships of 544,000 gross tons, still well below the record highs established in May and June 1942. This increase was due entirely to increased activity in the U. S. Strategic Area, where the losses mounted again to 84 ships of 407,000 gross tons sunk by U-boats. Over half of these losses occurred in the Caribbean Sea Frontier, where the main sore spots were the eastern approaches to Trinidad and the Windward Passage area. A group of about five U-boats achieved considerable success, especially against tankers, east of Trinidad. Twenty of the 23 ships sunk there were sailing independently. In the Windward Passage area 11 ships were sunk from convoys running between Key West and Trinidad and between Panama and Guantanamo. The activities of probably two U-boats off the Brazilian coast resulted in seven sinkings and brought Brazil into the war on the side of the United Nations. The coastal waters of the Atlantic from Nova Scotia to the tip of Florida were free from attacks by U-boats during the entire month of August.

The other significant trend of the month's operations was the resumption of large-scale attacks on the transatlantic convoys. In view of the reduced effectiveness of U-boats in the Eastern and Gulf Sea Frontiers, due to the start of convoying and the heavy aircraft coverage, it was natural that the U-boats would resume their attacks on the transatlantic convoys, especially in areas in the North Atlantic out of the range of land-based Allied aircraft. Over 20 ships of about 120,000 gross tons were sunk by U-boats in the Northwest Atlantic Area in August. The heaviest losses were suffered by Convoy SC 94, which lost 11 ships as a result of U-boat attacks.

In these attacks on convoys, the first indication of the presence of U-boats was often an HF/DF bearing, and these were of great assistance to escort commanders in appreciating the subsequent situation. Shipborne 10-cm radar (SG and Type 271) also proved a most efficient detector at night, and the quick action taken by escorts in many cases thwarted night attacks. This apparently influenced some of the U-boats to temporarily abandon their tactics of night surfaced attack and to attack submerged in daylight. As many as five ships were torpedoed by one salvo on a day attack, and to lessen the chance of such an event recurring instructions were issued in the third week of August to open out the distance between the columns of a convoy to about 1000 yards by day as well as by night.

The number of U-boats destroyed during August reached a new high for the war as 20 were sunk or probably sunk, 12 in the Atlantic, five in the Mediterranean, and three in the Pacific. Two U-boats were sunk by escorts of Convoy SC 94 and a U-boat was sunk in the Caribbean Sea Frontier for the first time. U-464, sunk by a U. S. PBY plane southeast of Iceland, turned out to be one of the new 1600-ton supply U-boats. These were used to refuel other U-boats at sea and thereby enabled them to extend their cruises. These supply U-boats were intended to stay at sea for as long as six months.

At the end of August, the coastal convoy system was further extended and New York included as one of the ports in the system. In September, New York also became the main western port for the transatlantic convoys, with HX and SC convoys beginning and ON convoys ending their passages there. Another new development in September was the establishment of a temporary reinforcing group whose primary objective was the destruction of U-boats rather than the immediate defense of shipping. This group consisted of ten British escorts.

The shipping losses to U-boats decreased slightly in September to 99 ships of 496,000 gross tons. The principal areas of attacks on shipping were in the eastern approaches to Trinidad and in the area to the north and south of the Equator between Freetown and Ascension Island. There was also con-

siderable activity along the convoy routes in the Northwest Atlantic as well as in the Gulf of St. Lawrence.

In the Northwest Atlantic Area, U-boats sank 20 ships of 110,000 gross tons. The chief sufferer on the North Atlantic convoy routes was ON 127, with which five or six U-boats were in contact for four days in succession. In the course of these attacks, two of which were made in daylight, 11 merchant ships and one escort were torpedoed, four of the ships managing to reach port.

The two North Russian convoys had to fight their way through incessant U-boat and aircraft attacks, losing 16 ships in all, eight to U-boats. Six very promising attacks were carried out by the escorts who were assisted by Swordfish aircraft from HMS *Avenger*. This was the first operation in which this type of escort carrier had taken part. The losses to U-boats in the Caribbean Sea Frontier in September 1942 were 27 ships of 130,000 gross tons, considerably less than in August. A notable feature of the operations around the Trinidad Area was the sinking of ten ships engaged in the valuable bauxite trade. With the tremendous increase in shipping to and from the South Atlantic, the Trinidad Area had become one of the largest shipping focal points in the Western Hemisphere. U-boat activity had increased accordingly and was highly successful at first. Lack of suitable long-range surface and aircraft restricted the distance that east-bound convoys could be escorted from Trinidad. Beyond the dispersal points the U-boats had good hunting.

Aircraft available in the Trinidad Area, especially the RAF Squadron 53 (Hudsons), were utilized to the utmost and reinforcement aircraft from other areas, including a specially trained "Killer" group of U. S. Army Air Force B-18's, were ordered into the area. Emphasis was placed on offensive operations, using sweeps over most likely U-boat locations and routes along which convoys passed. The results were rather encouraging in September as one U-boat was sunk and several other promising attacks were made. The situation became somewhat eased after September as the number of U-boats in the area started decreasing. Therefore, in just over nine months from their entry into World War II, the United States, by the institution of escorted convoys and the provision of air cover and air patrols, had achieved a high degree of immunity from U-boat attack in their coastal waters.

4.2 COUNTERMEASURES TO THE U-BOAT

4.2.1 Convoys

In January 1942, the U-boats transferred their attention from the transatlantic and East Atlantic convoys to the unescorted shipping in the West Atlantic. This is reflected in the fact that only 10 per cent of the shipping sunk by U-boats during the first six months of 1942 was in convoy when sunk. This proportion increased again to about 30 per cent during the period July to September 1942 when the bulk of U. S. coastal shipping was being convoyed and the U-boats were attacking the transatlantic convoys again.

It was realized during the early months of the war that convoying was the only solution to the heavy losses off the Atlantic Coast. However, the U. S. Navy, due to its commitments in transatlantic escort and in the Pacific, did not have enough escorts to start the convoying of coastal shipping at the beginning of 1942. To provide additional forces, 24 British antisubmarine trawlers were allocated for service on the American coast and ten British corvettes were turned over to the U. S. Navy. Further, the whole system of transatlantic escort was recast and all antisubmarine forces (U. S. Navy, Royal Canadian Navy, and Royal Navy) were pooled in a single cross-Atlantic convoy scheme. This resulted in a certain economy and released a limited number of U. S. destroyers.

With the forces thus available and with the increased production of antisubmarine ships in the United States, it was possible to start convoying in the Western Atlantic in May 1942. Coastal convoys between Norfolk, Virginia, and Key West, Florida, started running on May 14. By opening up the transatlantic convoy cycle, the British were able to divert enough forces to the Caribbean to start convoys, mainly for tankers, over the Trinidad-Halifax and Aruba-Curacao-Trinidad routes.

During July, the convoy system on the east coast was greatly extended, with convoys running between Trinidad and Key West by way of Curacao and Aruba. Convoys were instituted between Panama and Guantanamo to connect with the other convoys. Convoys were also started in the Gulf of Mexico and the Gulf of St. Lawrence.

At the end of August, convoys running in both directions between Curacao and Halifax and be-

tween Key West and Trinidad were discontinued, as were also the convoys between Hampton Roads and Key West. A new convoy system was started with convoys running between New York and Guantanamo [NG and GN], and between the latter port and Trinidad by way of Curacao [GAT and TAG]. Convoys were also started between New York and Key West [NK and KN].

During the five months from May through September 1942 about 1800 ships were convoyed monthly in the U. S. coastal convoys and only about 12 of these ships were sunk monthly by U-boats for a loss rate of less than 1 per cent per trip. During the first nine months of 1942, about 1000 ships were convoyed monthly in ocean convoys and about 15 of these ships were sunk monthly by U-boats for a loss rate of about 1½ per cent per trip. (It should be considered that the average voyage for these convoys is considerably longer than for the coastal convoys.) The convoy run to and from Russia was particularly hazardous during this period, with about 34 ships sailing monthly and about three of these being sunk monthly by U-boats for a loss rate of about 9 per cent per trip. In addition, these convoys suffered considerable losses from enemy air and surface craft attack.

The effect of convoying in reducing shipping losses is clearly illustrated by the experience in the U. S. Strategic Area during the first nine months of 1942. There were about 600 ships at sea in this area throughout this period. During the first six months, before extensive convoying of coastal shipping had started, only about 10 per cent of the shipping was in convoy. There were, on the average, about 30 U-boats at sea in this area during the first six months and each U-boat was sinking about 2.7 ships a month. About 20 per cent of the independent shipping and about 1 per cent of the convoyed shipping were sunk each month by U-boats.

During the next three months, after extensive convoying of coastal shipping had started, about 80 per cent of the shipping was in convoy. The average number of U-boats at sea in this area had increased to about 50, but each U-boat was only able to sink about 1.4 ships a month, about half as much as during the first six months. Thus, despite the fact that the loss rates for both independent and convoyed shipping had increased (about 35 per cent of the independent shipping and about 6 per cent of the convoyed shipping were sunk monthly by U-boats) during the last three months of this period, the efficiency of the average U-boat in sinking ships was halved. This was mainly due to the fact that about 40 per cent of the shipping was exposed, during the latter three months, to the much lower loss rate experienced by convoyed shipping instead of to the high loss rate experienced by independent shipping.

Another consequence of the shift from independent to convoyed shipping is the increased danger which the U-boat faces when he attacks a convoy. Only about 1½ U-boats were sunk monthly in the U. S. Strategic Area during the first six months of 1942, while 1½ were sunk monthly in the same area during the next three months, most of them by forces escorting convoys.

4.2.2 Aircraft

At the beginning of 1942, the U. S. Navy sent out all available planes and blimps to battle the U-boats along the coast. They were helped by the First Bomber Command, initial Army Air Forces contribution, which was activated in December 1941. The Army planes patrolled and escorted under the operational control of the Navy. A second Army Air Forces unit broke into the picture in June 1942. This was the Seasearch Attack Development Unit [SADU], based at Langley Field, Virginia, and assigned a combination mission: (1) to develop tactics and techniques for using antisubmarine devices, and (2) to conduct general seasearch. SADU had two British loaned B-24's (Dumbos I and II). In these had been installed two early British microwave sets known as DMS-1000 and equipped with the first airborne Plan Position Indicator [PPI] scopes. In addition to the Army and Navy flying, there was also patrolling by the Civilian Air Patrol [CAP], mostly within 100 miles from shore.

The flying hours by U. S. Army and Navy aircraft in the Eastern Sea Frontier increased from about 5000 hours in January 1942 to a peak of about 25,000 hours in July 1942. In the Gulf Sea Frontier, only about 7000 hours were flown in May 1942, when sinkings of ships were at their peak, as compared to 12,000 hours in July 1942. In both of these sea frontiers, the number of U-boats at sea decreased rapidly after July 1942. In the Caribbean Sea Frontier, the number of flying hours increased from about 5000 in April 1942 to almost 10,000 in September 1942, when the number of U-boats at sea there started decreasing.

U. S. aircraft made about 30 attacks a month on U-boats during this period, varying from about 12 a

month during the first four months of 1942 to about 15 a month during the next five months. About 20 per cent of these attacks resulted in some damage to the U-boat, while only about 2 per cent of the attacks resulted in the sinking or probable sinking of the U-boat. The average height at which these attacks were made was about 150 feet. The depth bombs used were generally set for a depth of 50 feet at the beginning of this period (too deep for a surfaced U-boat) but toward the end of 1942 most of the attacks were made with settings of 25 feet. In addition, bombs were fitted with flat noses in order to reduce their forward motion under water and also to reduce ricocheting.

At about the beginning of 1942, Coastal Command aircraft had started using the 25-foot depth setting on their depth charges. The usual height at which their attacks were made was about 50 feet. Torpex-filled depth charges, which had a greater lethal radius, were introduced in April 1942. These factors produced a considerable improvement in the quality of Coastal Command attacks on U-boats. About 20 per cent of their aircraft attacks during this period resulted in at least some damage to the U-boat, while about 4 per cent of their attacks resulted in sinking the U-boat.

During the early months of 1942, when most of the U-boats were operating in the West Atlantic, Coastal Command aircraft started maintaining offensive patrols against transit U-boats. They operated both on the northern route, to the northward of Scotland, and in the approaches to the Bay of Biscay ports. During the first five months of 1942 only about 600 flying hours a month were spent on the Bay of Biscay offensive. This effort resulted in about seven sightings a month, enough to keep the U-boats submerged during the daytime.

In June 1942 Coastal Command introduced into operation about ten Wellington aircraft, fitted with the Leigh Searchlight and Mark II radar. These aircraft, operating in the Bay of Biscay, flew 190 hours in June, sighted seven U-boats, and attacked five of them. This success was achieved despite the fact that the night offensive in the Bay was considerably hampered by the presence of French fishing boats.

With the introduction of the Leigh Light Wellington in June 1942 the scale of the Bay offensive was greatly increased, with about 3400 flying hours being put into it monthly during the period from June through September 1942. About 30 sightings (9 per 1000 hours on patrol) and 23 attacks were made monthly during this period. It is believed that 43 per cent of all U-boat transits through the Bay were sighted and that five U-boats were destroyed during those four months. The immediate reaction of the enemy to the Coastal Command offensive in the Bay was an increased effort to intercept antisubmarine aircraft, to which Coastal Command replied by sending out Beaufighters to intercept the interceptors.

2.3 Scientific and Technical

The Germans were fully alive to the possibilities of meter-wave radar and they were aided by the capture of a Mark II radar set in Tunisia in the spring of 1942. They accordingly concluded that radar was responsible for the night attacks in the Bay of Biscay and tests in the summer of 1942 confirmed that the transmissions were easily detected by a single receiver and aerial. Admiral Doenitz ordered the speediest equipping of all U-boats with a makeshift equipment. The aerials of wood and cable (Southern Cross Aerial) were easily made and the Paris firm of Metox turned out the R 600 receiver. The first U-boat German Search Receiver [GSR] was designed to detect meter radar and came into operation about October 1942.

Another new device introduced by the U-boats in the latter half of 1942 was Submarine Bubble Target [SBT] or "Pillenwerfer." These were tablets which were to be released by the U-boats when attacked by surface craft. The bubbles formed by the dissolving tablets produced false sonar targets which were intended to throw the attacking ships off the trail of the U-boat.

In the early months of 1942, a new form of passive defense against torpedo attacks, known as Admiralty Net Defense [AND], was being fitted to new merchant ships of speeds not less than 11 knots and not more than 15 knots. Early trials indicated that these nets would stop about 50 per cent of U-boat torpedoes fired at the ship.

In March 1942, the Hedgehog charges were made more lethal by filling them with Torpex, a new explosive which was, volume for volume, 1.7 times as powerful as TNT. About the middle of 1942, the U. S. Navy put into operation the "Mousetrap" projector, which fires a number of relatively small, fast-sinking charges equipped with contact fuzes and is suitable for installation on small antisubmarine

ships. As the light construction of these ships does not permit any great amount of deck thrust, the projector utilizes the rocket principle for launching. The projectiles are copies of the Hedgehog projectiles fitted with suitable rocket motors in the tail.

Magnetic Airborne Detector [MAD] was also developed during this period in order to enable aircraft to follow submerged submarines. This device detects the change in magnetic field produced by a submarine but its detection range is only about 500 feet.

1.2.4 Sinking of U-boats

The number of enemy U-boats sunk during this 9-month period was 78 (50 German, 17 Italian, and 11 Japanese). Forty of the U-boats were lost in the Atlantic (21 of them in the U. S. Strategic Area), 21 in the Mediterranean, 11 in the Pacific, two in the Barents Sea, one was mined in the Baltic, and three were lost under unknown circumstances.

Surface craft continued to be the main factor in sinking U-boats in all areas, accounting for 34 U-boats (44 per cent of the total number sunk) while coordinated attacks involving both surface and aircraft accounted for another six U-boats (8 per cent). Aircraft played a significant part in sinking U-boats, for the first time, accounting for 19 (24 per cent); all of these sinkings occurred in the Atlantic and Mediterranean. Submarines were an important factor in both the Mediterranean and Pacific, accounting for 14 U-boats (18 per cent of the total).

In the U. S. Strategic Area, the main scene of U-boat activity, there were about 360 surface craft attacks made on U-boats during this period. About 12 per cent of these attacks resulted in at least some damage to the U-boat while about 3 per cent of them resulted in sinking it. A British study of 106 surface craft attacks in the North Atlantic and Western Mediterranean during this period indicates that about 25 per cent of the attacks resulted in at least some damage to the U-boat while about 10 per cent of these resulted in sinking it.

1.3 SURVEY OF RESULTS

1.3.1 From the U-boat's Point of View

This was by far the most successful period of the war for the U-boats. The total world-wide losses amounted to 878 ships of 4,587,000 gross tons sunk by U-boats (about 98 ships of 510,000 gross tons sunk monthly). The main U-boat battle continued to be fought in the Atlantic where about 90 per cent of these losses occurred. The number of U-boats lost during this period was 78 (about nine a month) so that the world-wide exchange rate was 11 ships of 59,000 gross tons sunk for each U-boat sunk.

Japanese U-boats sank 76 ships during this nine-month period (48 in the Indian Ocean and 28 in the Pacific) while 11 U-boats were sunk (all in the Pacific) so that their exchange rate was about seven ships sunk for each U-boat sunk. In the Barents Sea Area, 15 ships were sunk by U-boats as against two U-boats sunk while in the Mediterranean, 17 ships were sunk as against 21 U-boats lost. Life was much more hazardous for U-boats in the Mediterranean than for those in any other area.

In the Atlantic, the main theater of activity, the average number of U-boats at sea was about 57, almost twice as many as during the previous period. These U-boats sank about 85 ships of 456,000 gross tons a month during this period, more than 2½ times as much as in the previous period. About 85 per cent of these losses occurred in the U. S. Strategic Area, where their main effort was directed against the weak spot off the east coast of the United States. The average U-boat in the Atlantic sank about 1½ ships of 8000 gross tons per month at sea, about 50 per cent more than the corresponding figure for the previous period. However, it should be kept in mind that this sinking rate was still far below that achieved during the period from July 1940 to March 1941, when the U-boat Aces were operating and the average U-boat was sinking four ships per month at sea.

The U-boats operating in the Atlantic were relatively safer during this period than at any other time in the war. Of the 57 U-boats at sea, about 4½ were sunk monthly so that the average life of a U-boat at sea reached a new high of 13 months. This meant that the average U-boat in the Atlantic, during this period, was sinking 19 ships of about 100,000 gross tons before it, itself, was sunk, the highest exchange rate of the war (about twice as high as during the previous periods).

This record exchange rate was achieved by concentrating the U-boat effort in the U. S. Strategic Area, of the United States, where the defenses were rather weak and the bulk of shipping unescorted. Of the 57 U-boats at sea in the Atlantic, about 37 were

in the U. S. Strategic Area, where they were able to sink 71 ships of 375,000 gross tons a month while only 2½ U-boats were lost monthly.

During the first half of 1942, the U-boats achieved their main successes in the Eastern and Gulf Sea Frontiers. The number of U-boats in these areas reached a peak in July 1942 when there were, on the average, eight at sea in the Eastern Sea Frontier and six in the Gulf Sea Frontier. However, by then the bulk of shipping was in convoy and surface and aircraft had each been making over two attacks a month on each U-boat. Under these conditions, the effectiveness of U-boats in sinking ships was greatly reduced, and the number of U-boats operating in these coastal regions decreased rapidly after July 1942. In the Caribbean, it was not until August 1942 that a corresponding level of attacks on U-boats was reached and the reduced effectiveness of the U-boats in sinking ships first became apparent in September 1942, when there was a peak of about 10 U-boats at sea there. The number of U-boats at sea in the Caribbean started falling off after September 1942.

It was natural, therefore, that as the combination of convoying and heavy air coverage reduced the effectiveness of U-boats along the East Coast of the United States, the U-boats would look for other weak spots in the Allied defenses. The most likely looking spot was the "gap" in the Northwest Atlantic Area where the U-boats could operate against the vital transatlantic convoys in a region outside the range of Allied air cover. The number of U-boats in this area had increased from about seven during the first half of 1942 to 11 in August and September while the shipping losses to U-boats in the Northwest Atlantic Area had mounted to over 100,000 gross tons in each of these months. It seemed likely that the crucial battle of the U-boat war would be fought against these convoys in the North Atlantic during the next period.

The Germans were in an excellent position to conduct an intensive U-boat campaign at the end of September 1942. The number of ocean-going U-boats available had increased from about 200 at the beginning of 1942 to about 350 at the end of this period. This was accomplished by commissioning about 200 new U-boats while only 50 were lost. In addition, many of the new U-boat commanders and crews had gained considerable experience and confidence as a result of their successful operations in the West Atlantic.

1.3.2 From the Allies' Point of View

Total shipping losses from all causes of the Allied and neutral nations reached the highest level of the war during this period, amounting to 700,000 gross tons a month, almost twice as high as during the previous period. Fortunately, the building rate of new shipping was also greatly increased, averaging about 515,000 gross tons a month. This increase reflected chiefly the great expansion in U. S. construction of shipping from less than 100,000 gross tons in January 1942 to almost 700,000 gross tons in September 1942. Consequently, the net monthly loss of shipping was only about 185,000 gross tons, slightly less than during the preceding period.

Of the 700,000 gross tons of shipping lost monthly, about 655,000 gross tons were lost as a result of enemy action. U-boats accounted for 510,000 gross tons a month (about 78 per cent of the total lost by enemy action), a much higher proportion than in the past. Monthly losses to enemy aircraft dropped to 67,000 gross tons (10 per cent of the total). Monthly losses to enemy surface craft were about 39,000 gross tons, while the monthly losses to mines were only about 11,000 gross tons.

The total shipping available decreased from about 33,300,000 gross tons at the beginning of 1942 to about 31,600,000 gross tons at the end of this period. Particularly serious was the heavy destruction of tankers during this period, 190,000 gross tons lost monthly as compared to 70,000 gross tons constructed monthly. The size of the tanker fleet declined by over 1,000,000 gross tons, or about 10 per cent of its size at the beginning of 1942.

The number of ships suitable for ocean escort, available to the Allies, increased from about 670 at the beginning of 1942 to 715 at the end of September. This was due mainly to an increase of about 60 in the number of destroyers. Twelve new auxiliary aircraft carriers were also completed during this period. However, the gravity of the U-boat situation at the end of this period resulted in a sizeable expansion in the construction program for 1943, with the U. S. Navy expecting to produce over 500 escort ships, more than half of which would be destroyer escorts (DE), designed especially for convoy escort and antisubmarine warfare.

Although the Allies had suffered extremely heavy losses in the Western Atlantic during this period, convoying and aircraft had succeeded in driving the

U-boats out of these coastal regions by the end of this period. The main problem facing the Allies during the next period was that of maintaining the flow of war material from the United States to England, in particular, that of assuring the safety of the North Atlantic convoys. It was becoming increasingly apparent that, although the defeat of the U-boats would not, of itself, win the war, the Allies could not possibly win the war without first defeating the U-boats.

Chapter 5

FIFTH PERIOD

LARGE WOLF PACKS BATTLE NORTH ATLANTIC CONVOYS

OCTOBER 1942–JUNE 1943

5.1 U-BOAT OFFENSIVE

DESPITE the fact that the U-boats had been driven from the coastal areas of the United States by the beginning of this period, the shipping losses to U-boats continued to run at the same high level as during the previous period. The Atlantic continued to be the chief area of U-boat activity with about 85 per cent of the shipping losses to U-boats occurring there. There were over 100 U-boats at sea in the Atlantic during most of this period. This enabled the enemy to conduct an intensive U-boat campaign in the Northwest Atlantic Area against the strategically important North Atlantic convoys and still maintain a number of subsidiary campaigns in other widespread areas (such as the Caribbean, Brazilian, Freetown, and Southeast Atlantic Areas) in an attempt to force the Allies to disperse their forces.

The total shipping losses to U-boats continued to be rather heavy in October 1942 as 93 ships of 614,000 gross tons were sunk. The intensity of the U-boat campaign against the transatlantic convoys increased with the number of U-boats in the Northwest Atlantic Area rising from 14 in September to 22 in October. These U-boats sank 24 ships with the bulk of the losses occurring in the "gap," the region outside the range of shore-based aircraft. Experience indicated that a convoy, not protected by aircraft, may be so disorganized by a concentrated attack and the resultant breaks in formation for rescue work and other adjustment that the escorts may become comparatively ineffective for either protection or offense. However, the presence, even for a few hours, of one or two aircraft has again and again prevented a concentrated attack from developing.

This was well illustrated during October. On the 4th, Convoy HX 209 was in some peril when about 300 miles south of Iceland. U. S. Navy Catalinas provided close escort for $15\frac{1}{2}$ hours and protective sweeps were laid on by seven aircraft from Iceland and three Fortresses from England. In the course of these operations the aircraft made nine sightings and carried out six attacks; the attack on the convoy did not develop. On the other hand, Convoy SC 104 was heavily attacked on the nights of the 13th and 14th when out of the range of aircraft and eight ships were torpedoed. On the following day there was a change for the better. The weather improved and air cover arrived enabling the surface escort to go over to the offensive and sink two U-boats.

Another development during October was the start of the expected U-boat operations in the Southeast Atlantic Area, near Capetown. This new "soft spot" was exploited by two groups, each of about six U-boats, which reached the Capetown area and eventually passed into the southern part of the Indian Ocean, where Japanese U-boats had previously achieved considerable success. These groups sank 25 ships in the Southeast Atlantic Area during October. All of these ships were independently routed and some carried rather valuable cargoes.

However, some of the heavy shipping losses suffered in October and November may be charged to the success of Operation Torch, the landings in North Africa early in November 1942. A great deal of merchant shipping and many escorts were naturally diverted from their normal use in October, when the foundations were firmly laid for the achievement of the safe arrival of the first military convoys. In addition, the enemy disposed an abnormally large proportion of his Atlantic U-boat force east of the Azores and Madeira. This suggests that, in a broad sense, the German command had appreciated the likelihood of an Allied attack on Africa. One consequence directly resulting from this redisposition of U-boat forces was that Convoy SL 125 was severely mauled, losing 12 ships during a 4-day pursuit by a pack of about six U-boats. However, the pursuit was abruptly dropped before it drew the U-boats away from the area southwest of Portugal; it may have been regarded as of greater importance that they should stay there and reconnoiter than that they should further pursue an ordinary trade convoy.

Despite the fact that convoys of the expeditionary

forces had to pass through concentrations of 30 to 40 U-boats before reaching Gibraltar, no U-boat successes were achieved against these convoys until after the assault troops had landed. The number of U-boats in the Western Mediterranean increased from about 10 on November 8 to about 20 on November 11. The losses to U-boats in Operation Torch amounted to only about 84,000 gross tons of shipping and six naval vessels. The total shipping losses from all enemy causes in this operation amounted to about 134,000 gross tons, against which can be offset a gain to the Allies of about 181,000 gross tons of serviceable tonnage acquired in French ports. In addition to the defensive success achieved against the U-boats in Operation Torch, the Allies also scored a notable offensive success, sinking 15 U-boats in the Mediterranean during November. A large factor in these victories over the U-boats was the heavy air cover provided, since aircraft from Gibraltar made 110 sightings and 61 attacks on the large concentration of U-boats.

In contrast to the successful landings in North Africa, world-wide shipping losses reached their highest point of the war in November 1942, as 862,000 gross tons of shipping were lost from all causes. U-boats also sank the greatest tonnage of the war in November, accounting for 116 ships of 712,000 gross tons. The tonnage sunk during October and November was swelled by the loss of a number of large, fast, independently routed ships which, on account of their speed, had been regarded as fairly safe from U-boat attack. Losses in the Northwest Atlantic continued at their high level as 26 ships of 141,000 gross tons were sunk there by U-boats. Losses in the Southeast Atlantic fell off slightly to 23 ships of 127,000 gross tons but shipping losses in the Caribbean and Brazilian Areas mounted again as the U-boats sank 34 ships of 210,000 gross tons there. These heavy losses in widespread areas occurred despite the intensive effort made by the U-boats in opposing the Allied landings in North Africa.

The shipping losses to U-boats in December 1942 were 62 ships of 344,000 gross tons, only about half the record total of November. This steep decline was probably due to the cumulative effect of various contributing factors, such as the concentration of U-boats in the Atlantic approaches to the Western Mediterranean and a consequent withdrawal elsewhere (particularly from the West and South Atlantic), the heavy bombing by Allied aircraft of the Biscayan U-boat bases, and some effective work by surface and air escorts on the North Atlantic routes, as well as adverse weather and some luck in routing. The enemy attributed the smaller sinkings to bad weather.

Only one convoy, ONS 154, suffered heavy losses in the North Atlantic. This convoy was given a southerly route and was attacked by a pack of about 20 U-boats as it drew out of the range of air cover. These U-boats followed the convoy for four days and sank 14 ships. This again demonstrated the immense importance of efficiently combining surface and air escort and indicated that surface escorts are physically incapable of warding off concerted attacks by a pack of U-boats which outnumbers them by more than a 2 to 1 ratio. In selecting convoy routes at this time, the advantage of the northerly route within the range of air cover from Iceland had to be balanced against the increased time of the trip due to greater distance and worse weather. In addition the bad weather reduced the efficiency of the escorts.

The shipping losses to U-boats in January 1943 dropped to only 37 ships of 203,000 gross tons, less than in any month of 1942. Bad weather was the primary factor responsible for this reduction and it was recognized that the gravity of the U-boat threat was much more serious than indicated by the low shipping losses. The fate of a tanker convoy bound from Trinidad to Gibraltar seemed a truer index of the strength of a U-boat pack operating in favorable conditions at the beginning of 1943. Convoy TM 1, made up of nine tankers and four escorts, lost seven tankers as a result of U-boat attacks, all well outside the range of shore-based aircraft. This was the highest proportion of ships sunk from any convoy by U-boats during the war.

Of the 100 or more U-boats at sea in the Atlantic on any one day, over a third were operating in the Northwest Atlantic Area. The U-boats were concentrating against the North Atlantic convoys which carried cargoes of immediate importance for military operations. Grand Admiral Doenitz had become supreme commander of the German Navy and it was becoming evident that the critical phase of the U-boat war in the Atlantic was approaching.

To meet to some extent the need for shore-based air cover for Atlantic convoys, the Allies planned to introduce Very Long Range (VLR) aircraft with an endurance of 2000 to 2500 miles. Some flying was also done from Greenland although weather conditions

were a severe handicap. Continuous shore based air cover was available between Gibraltar and Freetown.

In February 1943 the U-boat effort in the North Atlantic increased in intensity. The world wide shipping losses to U-boats increased to 63 ships of 359,000 gross tons, with about half these losses occurring in the Northwest Atlantic Area. Two of the North Atlantic convoys were heavily attacked by packs of about 20 U-boats. Convoy SC 118 lost 12 ships to U-boat attacks early in the month, seven of them during a period of three hours. However, at least two U-boats were sunk and six damaged during this action. Convoy ON 166 suffered the loss of 14 ships over a period of five days as a result of U-boat attacks outside the range of shore based aircraft. The enemy was concentrating his forces in an effort to interrupt the flow of supplies from America to Great Britain and the U-boats were displaying increased boldness in attempting to achieve this objective. However, about 20 VLR aircraft had become operational in February 1943.

In March 1943 the world wide shipping losses to U-boats mounted to 107 ships of 627,000 gross tons. The tempo of the U-boat offensive against the transatlantic convoys increased as the number of U-boats in the Northwest Atlantic Area rose to about 50. These U-boats sank 38 ships in that area, a high for the war, and an additional 15 ships were sunk in the adjacent Northeast Atlantic Area. The enemy's resources were such that he was also able to maintain offensives in the South Atlantic and in the Caribbean and Azores Areas. About two-thirds of the tonnage sunk by U-boats during March was in convoy when sunk and the figure of over 400,000 gross tons of shipping sunk in convoy by U-boats during the month was a record for the war. The main reason for the large increase in tonnage sunk in convoy was an increase in the number of convoys attacked and not a weakening in the protective value of the escorts.

The intensity of the U-boat effort in the North Atlantic during March is clearly indicated by the attacks on four consecutive eastbound transatlantic convoys. The U-boats generally outnumbered the escorts by about two to one and were able to torpedo 30 ships from these four convoys, in addition to eight stragglers. Convoy SC 121 was badly scattered by heavy weather and lost five ships in convoy and seven stragglers. Convoy HX 228 lost four ships to the U-boats but the escorts were able to sink two U-boats in one of the dramatic incidents of the U-boat war. After an attack on the convoy, HMS *Harvester* sighted a U-boat and rammed it at about 26 knots. The U-boat hung under the stern and could not be dislodged for about ten minutes. The FFS *Aconit* finished off the damaged U-boat. In spite of considerable damage, HMS *Harvester* was able to proceed on one engine for several hours until she became completely disabled and was torpedoed. The FFS *Aconit* then sank the U-boat which had destroyed HMS *Harvester*.

Convoys HX 229 and SC 122 were routed closely together and ran into a concentration of about 40 U-boats, the largest pack employed up to that time, losing 20 ships to the U-boats. On the night of March 16-17, 13 ships were sunk when the convoys were about 850 miles from the nearest air bases. The following day the convoys received some air cover from VLR aircraft, with one plane sighting six U-boats. In all, 54 sorties were flown in defense of these two convoys resulting in 32 sightings and 21 attacks. The U-boats were finally forced to disengage on March 20 and this date may well be considered as the turning point in their offensive power as sinkings of merchant vessels were at a much lower rate thereafter.

Although the shipping losses in March were very heavy, there were signs that the situation in the North Atlantic was improving. Advances had been made towards the provision of continuous air cover for transatlantic convoys by the increased use of VLR aircraft from Newfoundland, Iceland, and England and by the introduction of escort carriers and Merchant Aircraft Carriers (MAC) ships. MAC ships were merchant ships whose decks were converted so that they could carry four Swordfish aircraft which could take off and land. The USS *Bogue*, the first U. S. escort carrier, started operations as an escort for the North Atlantic convoys during March. At the Atlantic Convoy Conference held in Washington in March, it was agreed that, starting in May, the United Kingdom and Canada should be responsible for the security of convoys across the North Atlantic, the United States providing certain air and sea forces to help them. It was also decided to set up a unified air command in Newfoundland corresponding to the Coastal Command system. The United States was to base a substantial force of VLR aircraft in this region, which, together with the VLR Liberators of the RCAF, were to close the gap in the North Atlantic.

Although the number of U-boats at sea continued at the same high level in April 1943, the shipping loss

was greatly reduced with the U-boats sinking 56 ships of 328,000 gross tons. The shipping losses to U-boats in the Northwest Atlantic Area in April were only 18 ships of 108,000 gross tons, less than half the March record. Ten ships were sunk by U-boats in the Freetown Area and Japanese U-boats sank six ships in the Southwest Pacific, off the east coast of Australia.

Accompanying the decrease in shipping losses there was a considerable increase in the number of U-boats sunk, 17 being sunk in the Atlantic for a record high to that date. April also marked the first sinking of a U-boat in which planes from an escort carrier took part. A plane from HMS *Biter* found and attacked a U-boat which HMS *Pathfinder*, one of the escorts, sank.

A more satisfactory criterion that the U-boat offensive strength had passed its peak was the fact that, for the first time, U-boats failed to press home attacks on convoys when favorably situated to do so. In none of the attacks on transatlantic convoys did the enemy succeed in obtaining anything like the upper hand. All of the U-boats' efforts tended to avoidance of detection and, once it was apparent that they had failed in this endeavor, they seldom pressed home their attacks. There were five Support Groups operating in the North Atlantic during April, two of them having their own escort carrier, and the number of VLR aircraft available had risen to over 30. More important, there was a noticeably enhanced standard of group training, better use of HF/DF was made, and cooperation between surface and air components of the escorts was greatly improved.

May 1943 seems to have been the crucial month in the Battle of the Atlantic. The number of U-boats at sea in the Atlantic reached a peak of about 120, with about half of these U-boats concentrated in the Northwest Atlantic Area. The decisive battle took place at the beginning of the month between Convoy ONS 5 and a pack of about 40 U-boats. On May 4, when HF/DF activity indicated that the U-boats had made contact, the convoy consisted of about 30 ships and four stragglers. The average number of escorts present during the battle was about eight. Despite the bad weather, aircraft of the Royal Canadian Air Force provided air cover during the afternoon of the 4th and carried out two promising attacks, one of which is considered to have sunk the U-boat. The U-boats started attacking shortly after midnight and 12 ships were sunk on May 5, about half during the night and half during the next day. Due to bad weather, air cover was provided for only an hour on the morning of the 5th. By midnight the weather had become calm and foggy and from then onwards the escorts had the upper hand. In the course of the night they frustrated about 24 attacks by the U-boats without suffering any losses and, in addition, inflicted heavy losses and much damage on the enemy. At least five U-boats are considered to have been sunk by the escorts during the battle. The U-boats broke off the action in the course of the day and did not renew it. In no succeeding convoy operation did the enemy display the same determination.

Several other convoys were threatened in the first half of the month but no serious losses were suffered and the toll of U-boats mounted steadily. After May 17, no ship was lost in the Atlantic north of 45° north latitude. The world wide shipping losses to U-boats in May 1943 decreased to 50 ships of 265,000 gross tons. Only 11 ships were sunk in the Northwest Atlantic Area while diversionary U-boats sank 15 ships in the Freetown and Southeast Atlantic Areas.

The most notable feature of the operations during May was the success of our offensive against the U-boats. The number of U-boats sunk during the month reached a record high of 41, almost twice the previous high, with 38 of the sinkings occurring in the Atlantic. A record number of 15 were sunk in the Northwest Atlantic Area and the number sunk in the Bay of Biscay also reached a new high of 11. Shore based aircraft accounted for over half the U-boats sunk during the month while carrier based aircraft participated in three of the attacks in which the U-boat was considered to have been sunk.

By the end of May it was clear that the U-boats had been decisively beaten as the number at sea in the Atlantic dropped to about 85, with no small proportion of the reduction due to sinkings of U-boats. The U-boats could not afford to suffer the heavy losses experienced in May and they were forced to withdraw from the battle against the vital North Atlantic convoys. This was an admission of defeat in itself. It should be noted that superior leadership and tactics, quick initial action, and well coordinated attack and defense played as much of a part in the defeat of the U-boats as did concentration of forces at the decisive points and weapon superiority.

By June 1943 the U-boats had retired from the main battlefield of the North Atlantic convoy routes and a considerable number had moved into the

Azores Area, outside the range of shore-based aircraft. As a result, June was an interim phase for the U-boats and they were able to sink only 20 ships of 96,000 gross tons during the month, the smallest amount of shipping sunk by U-boats since November 1941. Not a single ship was sunk in the Northwest Atlantic Area during June and only seven ships were sunk by U-boats in the whole Atlantic. Seven ships were sunk in the Indian Ocean and six in the Mediterranean.

The offensive against the U-boats continued throughout June, but as the opportunities to attack U-boats were rarer due to their redisposition, only 19 were sunk during the month. Aircraft continued to play an outstanding part, sinking ten U-boats, two by carrier-based aircraft from the USS *Bogue* in regions where the U-boats thought they would be safe from shore-based aircraft. The 2nd Escort Group, led by HMS *Starling* sank three U-boats during the month and clearly demonstrated that a well-trained escort group could deal effectively with a U-boat. On June 2, this escort group made contact with U-202. Twelve depth-charge attacks were made without positive evidence of success, so it was decided to hunt the U-boat until its batteries were exhausted and it had to surface. One ship maintained contact while the remainder formed a square patrol. Despite every maneuver and artifice, including the release of 19 SBT's, the U-boat was compelled to surface after contact had been firmly held for 11½ hours. She was immediately attacked by gunfire and the crew abandoned ship. On June 24, the 2nd Escort Group, acting as a striking force in cooperation with aircraft engaged in the Bay offensive, destroyed two more U-boats in the space of 9 hours.

As the period closed, it was apparent that the U-boats had been decisively defeated in the battle against the North Atlantic convoys. The Allies had meanwhile taken the initiative and joined battle in the approaches to the Bay of Biscay, through which all U-boats must pass to and from their bases.

5.2 COUNTERMEASURES TO THE U-BOAT

5.2.1 Convoys

There were only a few minor changes in the convoy system during this period. The landings in North Africa in November 1942 resulted in the temporary suspension of sailings of the Sierra Leone and Gibraltar convoys for several months due to lack of escorts. Shortly after these landings new convoys were started between the United States and the Mediterranean (designated UG and GU) to supply Allied forces in North Africa. The U. S. Coastal Convoy System was extended to Brazil in December 1942 following increased U-boat activity in that area.

There were, however, a number of extensive changes in the routing of independent shipping. At the beginning of this period, the Allies were forced, by a concentration of U-boats between Natal and Dakar, to discontinue the route to the Red Sea and India via the Atlantic and the Cape of Good Hope. Shipping was instead routed via the Panama Canal and Cape Horn to Capetown. However, after the U-boats had started operations in force around Capetown, the bulk of the Indian Ocean traffic was routed transpacific from Balboa south of New Zealand to Fremantle for onward routing to destination. This route through the South Pacific proved entirely safe. There have been losses in the Indian Ocean due to raiders and U-boats but, in general, this transpacific route was so successful that it was maintained until the Mediterranean was considered open in July 1943. It can be seen that there was a considerable gain in effective shipping due to the use of the short Mediterranean route instead of the long circuitous route across the Pacific.

During this period, the main efforts of the U-boats were concentrated against convoyed shipping, in particular against the North Atlantic Trade Convoys (ON, ONS, HX, and SC). The proportion of tonnage sunk by U-boats which was in convoy when sunk, increased from about 30 per cent during the last three months of 1942 to 67 per cent in March 1943 and then dropped back to about 25 per cent in June 1943 after the U-boats had withdrawn from the North Atlantic convoy routes. About 720 ships sailed monthly in the North Atlantic Trade Convoys and about 21 of these ships were sunk monthly by U-boats, so that the loss rate was about 3 per cent per crossing. This loss rate reached a peak of about 5 per cent in March 1943. By June 1943 the U-boats had been forced to withdraw and 850 ships arrived safely in these convoys without the loss of a single ship to the U-boats.

The strategy of the U-boats in their battle against the North Atlantic convoys was to maintain patrols in positions designed to find convoys at a time when

they were about to leave the protection of air cover, and it was in this gap that the U-boats scored their greatest success. There were three main U-boat formations for attacks on convoys, namely (1) Patrol line, (2) Reconnaissance sweep, and (3) Attack formation. In the first, U-boats up to perhaps 25 in number are spread about 20 miles apart on a given line of bearing across the convoy routes. Each U-boat patrols at slow speed on either side of and at right angles to the line, not going further than half an hour's run from it. If the U-boat sights a convoy she must report it to Admiral, U-boats, who passes the signal to the other U-boats in the line. This Patrol line formation is a pool from which groups of U-boats may be detached for any given duty, such as an attack on a convoy or a Reconnaissance sweep of an area through which a convoy is expected to pass.

For the Reconnaissance sweep formation, Admiral, U-boats, signals the limits of the area to be swept, the time at which the sweep is to start, and the U-boats which are to take part. The U-boats ordered to the area, the limits of which may be 150 miles apart, proceed at a speed of about 10 knots on parallel courses and spread about 25 miles apart. When one of the U-boats has established the position of the convoy, a group of U-boats are ordered by Admiral, U-boats, to take up an attack formation. These U-boats may be formed up into a semicircle around the line of approach of the convoy. Once the order to attack is given, there is no such thing as coordinated action between the U-boats, though they may keep in touch with each other by radio. Each U-boat attacks at its discretion. The U-boats continue their attacks until ordered by Admiral, U-boats, to break off.

An analysis of attacks by U-boats on the North Atlantic convoys at about the beginning of this period indicated that about 70 per cent of the attempted attacks were frustrated by the escorts. About two ships were torpedoed in each successful attack. In only about half the successful attacks did the U-boat escape detection. Radar was responsible for more than half the cases in which the U-boat was detected.

5.2.2 Aircraft

The primary function of aircraft in the defense of convoys was the prevention of the gathering of U-boat packs capable of making destructive attacks. This function is accomplished in two ways. First, as a pack is gathering on a trailed and reported convoy, protective sweeps far ahead and to the flanks of the convoy enable aircraft to make killing and damaging attacks or at least to force U-boats to remain submerged at slow speed sufficiently long to delay the formation of an effective pack. Second, through keeping the trailing U-boats, on which the others are homing, submerged, aircraft can break the enemy's contact, enabling the convoy to escape by a change of course.

What the U. S. Navy needed in late 1942 was more long-range bomber coverage. The U. S. Army was anxious to help and set up the 1st Anti-Submarine Army Air Command in October 1942. This was an expansion of the 1st Bomber Command. Two antisubmarine squadrons were sent to England in December 1942. Early in February 1943 they operated in the Bay of Biscay and in March 1943 the two squadrons were ordered to Port Lyautey, Morocco, where they were to help the U. S. Navy protect the Mediterranean Approaches. By the end of this period two other U. S. Army squadrons had been sent to England while two U. S. Navy squadrons were operating from Iceland under Coastal Command.

When the U-boats started using GSR at the beginning of this period in October 1942 the need for microwave radar became more urgent. As a stop-gap 11 DMS-1000's were crash-built at a U. S. laboratory and rushed into British service. By the end of 1942 the U. S. Navy's AN/APS-2 [ASG] radar (S-band) was coming into service. The U. S. Army equivalent was the SCR-517.

The first effect of the introduction of GSR was a sharp reduction in the effectiveness of the aircraft offensive in the Bay of Biscay. The U-boats could detect radar-fitted aircraft ranges which allowed them ample time to dive and the number of sightings and attacks on U-boats dropped sharply. This lull lasted through January 1943. Only four sightings per 1000 hours on patrol were made during this four-month period, as compared to nine during the previous four-month period, when the number of U-boat transits was actually smaller. The search receiver for Mark II ASV enabled the U-boats to make safe night passages across the Bay and only 15 per cent of the transits were sighted. No U-boat is considered to have been sunk by any of the attacks made in the Bay during this period.

This situation was changed by the introduction of Mark III ASV (S-band) on Allied aircraft in Febru-

ary and March 1943. This set operated on a much shorter wavelength (10 cm) and could not be detected by the R 600 GSR. The proportion of aircraft approaches undetected by U-boats rose and consequently the sightings and attacks began a steady increase. This period of increased productivity in the Bay offensive lasted through July 1943. About 5500 hours were flown monthly during this 6-month period with about 61 sightings and 33 attacks made monthly. About five U-boats were sunk monthly as a result of this offensive. The average number of sightings per 1000 hours on patrol jumped to 11 and about 60 per cent of all transits were sighted during this period.

The German High Command had no idea as to what caused this huge increase in sightings and attacks and after running into several blind alleys in attempting to solve the problem, they were forced to make a number of changes in U-boat tactics. The first step was the strengthening of the antiaircraft armament of U-boats. This development first became apparent in April 1943 when on a number of occasions U-boats, sighted by aircraft, stayed on the surface and fought back using their antiaircraft guns. Although a number of aircraft were lost as a result of this measure, it did provide aircraft with a much larger proportion of surfaced targets and increased their chances of sinking a U-boat. Four U-boats that stayed up and fought back were sunk in April and nine such U-boats were sunk in May.

During the spring of 1943, the night-flying Wellingtons, equipped with Leigh Lights and Mark III ASV, made night surfacing in the Bay so hazardous for the U-boats that they changed their policy to one of surfacing in the daytime to charge batteries and renew their air supply. This, in turn, produced the period of greatest productivity in the campaign during May, June, and July 1943, with the result that during the last two of these months every U-boat transit was sighted once on the average. May 1943 was a record month for Coastal Command aircraft with the squadrons in the United Kingdom, Iceland, and Gibraltar accounting for 243 sightings and 136 attacks, 17 of which are considered to have been lethal. One of the U-boats sunk in May was the victim of the first rocket attack against U-boats. This attack was made by a Swordfish aircraft.

The next indication of a change in U-boat tactics was the sighting of five U-boats making the transit of the Bay in company on June 12. From then onwards most of the U-boats sighted were in packs of from three to five. Although this change should have no effect on the number of U-boats sighted, the number attacked will be less as each aircraft can normally only attack one U-boat. This effect appeared in June when there were 60 sightings in the Bay but only 28 attacks. The other advantages of this change, for the U-boats, are that they will have a better chance of seeing aircraft, they will have much stronger antiaircraft fire support, and it will be easier to provide fighter protection for them. Admiralty reacted immediately to this measure by sending surface craft hunting groups into the Bay to cooperate with aircraft and to follow up aircraft attacks. If the surface craft arrive at the scene of the attack quickly enough, several U-boats will be pinned down and the search should be easier. This countermeasure resulted in two of the U-boat kills made by the Second Escort Group in June. In addition, Mosquito fighters were sent into the Bay in June to operate against German aircraft covering the U-boats.

Aircraft finally came into their own as an offensive power during this period. The 25-foot depth setting was in general use and, especially during the later months, planes were able to attack U-boats still on the surface. About 60 aircraft attacks were made monthly on U-boats during this period, with about 25 per cent of the attacks resulting in at least some damage to the U-boat, while over 10 per cent of the attacks proved lethal. In addition aircraft were used to bomb U-boat bases and lay mines near them. These operations dislocated the servicing facilities at the bases and increased the turnaround time of U-boats operating from these bases.

5.2.3 Scientific and Technical

The main scientific battle during this period continued to center about radar. As we have seen, the Metox R 600 GSR was able to detect Allied meter-wave radar. The Allied countermeasure to GSR was the introduction of short-wave (S band 10 cm) radar about February 1943. This was made possible by the British invention of the strapped magnetron in the spring of 1940 which enabled sufficient power to be produced to make use of the shorter wavelengths practical. The Metox GSR was particularly unsuited to detecting these short wavelength radar transmissions and the number of aircraft attacks on U-boats increased sharply. The Germans had no idea of what

was causing the trouble and, suspecting supersonic modulation, they fitted GSR sets with a visual tuning indicator of the Magic Eye type. As this did not prove to be of any help they explored other blind alleys, suspecting infrared detection or intermittent operation of radar sets, without finding any solution during this period. The best the Germans could do was the fitting of a permanent GSR aerial, which did not have to be dismounted before diving, on some U-boats. Meanwhile it was evident in May and June 1943 that there was a progressive lessening of confidence in GSR on German U-boats. Radar was fitted on some U-boats, apparently primarily as an offensive weapon against shipping in low visibility. However, there was a great reluctance to use radar for fear of being detected by a hypothetical Allied search receiver. Radar decoy balloons were also used by some U-boats in an attempt to produce a large number of false targets.

A similar lack of appreciation of the situation was apparent in the U-boat's attitude toward HF/DF. As the new technique of using shipborne HF/DF was learned and applied, the successes became more frequent, and by November 1942 HF/DF was accepted as an essential part of the equipment of escort craft. The U-boats overrated the accuracy of shore-based HF/DF, but for a long time they underrated, indeed ignored, the danger of shipborne HF/DF. This was reflected in their communications, which seemed to be conducted on the principle that radio silence was to be strictly kept until contact was made with the convoy, but completely relaxed once contact was made. In other words, they were afraid of revealing their dispositions but saw no danger from the transmissions of individual U-boats once the battle was joined. During the attacks on Convoy SC 118 in February 1943, for example, the U-boats concerned made 108 transmissions during a period of 72 hours.

During this period several ships were saved by AND, the torpedoes either being stopped by the nets or exploding in them. There were six successful Hedgehog attacks during this period and it appeared that the numerous early difficulties with this weapon had been overcome and it was beginning to show some signs of its theoretical lethality.

It had become apparent in 1942 that some device was needed to enable attacking ships to maintain contact with deep U-boats to shorter distances. To meet this need the Q attachment was developed. It consisted of a small special sonar projector of high frequency, attached to the main projector below it and tilted down about 45°. Trials during this period indicated that good echoes could be obtained from targets within an angle of 45° from the horizontal.

The expendable radio sono-buoy was developed during this period to enable aircraft to maintain contact with a submerged U-boat. It could be dropped from an aircraft and contained a hydrophone which would listen to U-boat noises and a radio transmitter which would transmit the noises received to the plane. The service life of a sono-buoy was about four hours.

5.2.4 Sinkings of U-boats

The number of U-boats sunk or probably sunk during this critical period averaged about 19 a month, hitting a peak of 41 in May 1943. The total number sunk during this period was 168, more than twice the number sunk in any previous period. Of these, 128 were German, 18 Italian, 18 Japanese, and four were Vichy French.

There were 112 U-boats sunk in the Atlantic during this period, 43 of these in the Northwest Atlantic Area and 25 in the Bay of Biscay. There were 37 U-boats sunk in the Mediterranean, 15 during November 1942, the month of the North African landings. The 18 Japanese U-boats were all sunk in the Pacific.

This was the first period of the war in which aircraft were the leading killers of U-boats, sinking 76 U-boats (45 per cent of the total) alone and another 10 (6 per cent) in cooperation with surface craft. Ten of these 86 successful aircraft attacks involved carrier-based aircraft. Ships accounted for 59 U-boats (35 per cent) and submarines for 17 (10 per cent).

The quality of surface craft attacks continued to improve. About 60 attacks were made monthly on U-boats in the Atlantic and Mediterranean and about 25 per cent of these surface craft attacks resulted in at least some damage to the U-boats, while 10 per cent of these attacks resulted in the sinking of the U-boat.

5.3 SURVEY OF RESULTS

5.3.1 From the U-boat's Point of View

This was the crucial period of the war for the U-boats, the one in which they made their supreme effort and were decisively defeated. The world-wide shipping losses to U-boats were about 30 per cent

lower than during the preceding period, as about 67 ships of 391,000 gross tons were sunk monthly by U-boats, with about 85 per cent of these losses occurring in the Atlantic. The number of U-boats sunk throughout the world was about 19 a month, more than twice as many as during the previous period. The world-wide exchange rate was, therefore, only about 3½ ships of 21,000 gross tons sunk by the average U-boat before it, itself, was sunk. This exchange rate was only one-third as large as it had been during the previous period.

Activity in the Mediterranean was greatly increased as 44 ships were sunk by U-boats and 37 U-boats were sunk. U-boat operations in the Mediterranean were, in many cases, auxiliary to the military operations in North Africa. In the Indian Ocean, German and Japanese U-boats sank 25 ships, half the total in the previous period, without suffering any losses. Japanese U-boats sank 19 ships in the Pacific and suffered the loss of 18 U-boats, an extremely unprofitable return.

In the Atlantic, the scene of the main battle, the average number of U-boats at sea during this period was 104, higher than in any other period of the war. These U-boats sank about 57 ships of 344,000 gross tons monthly, about one-third of these sinkings occurring in the Northwest Atlantic Area. This meant that the efficiency of U-boats reached a new low for the war as the average U-boat sank only about one-half ship of 3200 gross tons per month at sea, only about one-third the results achieved in the previous period. This indicated that the U-boats' campaign of wolf-pack attacks against the North Atlantic convoys had failed to maintain the average U-boat effectiveness at its previous high level. The U-boats were very rarely able to completely overwhelm the escorts of the convoys and consequently the use of large wolf packs of over 20 U-boats proved relatively inefficient. In addition, when the U-boats had to operate against convoys which were given air coverage, their wolf-pack operations broke down completely as they depended upon surfaced U-boats to keep contact with the convoy and to home the other U-boats.

In addition to the reduction in its efficiency, the average U-boat in the Atlantic found life more hazardous during this period than in the preceding period. This marked the first time in the war that the trend of increasing safety for the U-boat was reversed. About 12½ U-boats were sunk monthly of the 104 U-boats at sea in the Atlantic, so that the average life of a U-boat at sea in the Atlantic during this period was about 8½ months, about one-third less than in the previous period. The main factors causing this shorter average life for U-boats were the increased effectiveness of Allied aircraft and the fact that the U-boats were exposing themselves to increased attacks by surface escorts by concentrating against convoyed shipping.

These figures indicate that the average U-boat in the Atlantic during this period was sinking only about 4½ ships of 28,000 gross tons before it itself was sunk. This exchange rate was the lowest of the war to that date and only one-fourth as high as the record exchange rate achieved in the previous period. This low exchange rate plus the fact that, in the Atlantic, the number of U-boats sunk in May 1943 was almost as large as the number of ships sunk by U-boats, must have convinced the Germans that they could not continue the battle against the North Atlantic convoys and they disengaged. The average number of U-boats at sea in the Northwest Atlantic Area dropped from 60 in May to 20 in June 1943.

The expansion of the German U-boat fleet was definitely slowed down during this period. Bombing of construction yards had kept new construction at about the same level as in the previous period, with about 20 new U-boats being commissioned monthly. About 128 German U-boats are considered to have been sunk during this period and a number of others decommissioned. Consequently, the available number of German U-boats increased from about 350 at the beginning of this period to about 400 at the end of the period. This huge fleet still constituted a considerable potential threat, but many experienced officers and crews had been lost during this period, and the heavy losses suffered by the U-boats must have had an adverse effect on enemy morale.

5.3.2 From the Allies' Point of View

Total shipping losses of the Allied and neutral nations were about 491,000 gross tons a month during this period, about 30 per cent less than during the preceding period. Construction of new merchant shipping reached a new high of about 1,026,000 gross tons a month, more than twice the total monthly losses. Consequently, the net monthly gain of shipping was about 535,000 gross tons. This was the first period of the war in which new construction of ship-

ping exceeded the total losses. The total shipping available increased by almost 5,000,000 gross tons during this period to a level of about 36,500,000 gross tons. It appeared that the shipping crisis in the war had definitely passed, as it seemed extremely unlikely that the shipping losses would ever exceed the million gross tons being constructed monthly. The main problem facing the Allies at the end of this period was to keep the shipping losses down to a minimum so that supplies could be built up quickly in England for the invasion of the continent.

Of the 191,000 gross tons of shipping lost monthly, about 136,000 gross tons were lost as a result of enemy action. U-boats accounted for 121,000 gross tons a month, about 90 per cent of the total lost by enemy action. Losses to enemy aircraft, surface craft, and mines were all considerably lower during this period than in the preceding one.

The number of ships suitable for ocean escort, available to the Allies, had increased from about 715 at the beginning of this period to about 950 at the end of June 1943. This included about 50 new destroyer escorts [DE] as well as about 25 new escort carriers [CVE]. This increased number of escorts and the new VLR aircraft that had become available placed the Allies, at the end of this period, in the position of having defeated the greatest efforts the U-boats could make. The Allies now had the opportunity of taking the offensive against the U-boats to prevent them from ever regaining the initiative.

Chapter 6

SIXTH PERIOD

AIRCRAFT DEFEAT U-BOATS' ATTEMPTED COME-BACK AND FORCE ADOPTION OF MAXIMUM SUBMERGENCE

JULY 1943–MAY 1944

6.1 U-BOAT OFFENSIVE

As a result of the heavy losses they experienced in their battle against the North Atlantic convoys during the previous period the U-boats withdrew from the North Atlantic and temporarily abandoned their wolf-pack tactics. After a marked lull in U-boat activity in June, the enemy made his first and most strenuous effort to regain the initiative in July 1943. The 85 U-boats at sea in the Atlantic were widely dispersed and simultaneous campaigns were conducted in regions that had been soft spots for the U-boats in the past, such as the Caribbean, Brazilian, and Freetown Areas. To withdraw from the strategically important North Atlantic was a confession of defeat, but the enemy must have anticipated a rich harvest from surprise attacks in comparatively lightly protected areas.

If so, the enemy was probably sadly disappointed. World-wide shipping losses as a result of U-boat action in July were only 41 ships of 241,000 gross tons, considerably less than the monthly average during the preceding period. The heaviest losses occurred in the Indian Ocean, mostly in the Mozambique-Madagascar Area, where 15 ships of 82,000 gross tons were sunk by U-boats while no U-boats were sunk. This was the highest monthly total of the war for shipping losses to U-boats in the Indian Ocean. About six German U-boats of the 1200-ton U-Kreuzer class were probably responsible for most of these sinkings.

About 15 U-boats operated in the Caribbean Sea and off the Brazilian coast as far south as Rio de Janeiro. They sank 19 ships during July, but were forced to pay a heavy price for these successes as nine U-boats were sunk by shore-based aircraft in these areas. This eliminated another soft spot from the list of areas where U-boats felt they could operate safely.

July 1943 was marked by the successful invasion of Sicily, which took place without the loss of any shipping to U-boats. Only five ships were sunk by U-boats in all of the Mediterranean at the cost of seven U-boats sunk by the Allies.

Despite the meager results achieved, the U-boats suffered the heaviest losses of the war in July 1943 as the world-wide total of U-boats destroyed during the month reached 46. This was the first month of the war in which the number of U-boats sunk exceeded the number of merchant vessels sunk by U-boats. Of the 46 U-boats sunk during July, 37 were destroyed in the Atlantic where aircraft experienced their greatest successes of the war. Shore-based aircraft destroyed 28 U-boats in the Atlantic while carrier-based aircraft accounted for another six. The aircraft from the U. S. escort carriers operated in regions outside the range of shore-based aircraft and were able to prevent the U-boats from achieving any successes in their attacks against the mid-Atlantic convoys. These attacks by carrier-based aircraft must have finally convinced the U-boats that they were no longer safe from air attack anywhere in the Atlantic.

Allied antisubmarine forces inflicted the greatest damage on the enemy in the Bay of Biscay and its approaches as 11 U-boats were sunk in the Biscay-Channel Area and another six in the Gibraltar-Morocco Area. Although aircraft crews had to face the increased antiaircraft fire of surfaced U-boats proceeding in formation during the daytime, this presented them with a large proportion of Class A targets and over 25 per cent of the attacks resulted in the sinking of the U-boat. The crowning success of the month occurred on July 30 when a whole group of three outward-bound U-boats was sunk, two by Coastal Command aircraft and the third by the Second Escort Group. Two of these three U-boats were supply U-boats, and this plus the loss of two other supply U-boats elsewhere severely curtailed later U-boat operations. This incident was also marked by one of the odd coincidences of the war when U-461 was sunk by the Sunderland aircraft U-461.

Four additional U-boats were sunk in the Bay of Biscay by Coastal Command aircraft during the first two days of August, and the U-boats were forced to change their tactics in making the transit of the Bay. They reverted to surfacing at night for the minimum time necessary for the charging of batteries and, in addition, hugged the coast of Spain to get as far as possible from Allied air bases.

The more cautious tactics adopted throughout the Atlantic in August 1943 marked the failure of the first attempted come-back by the U-boats. Only four ships were sunk by U-boats in the Atlantic during the month, all during the first week of August and all south of the Equator. The world-wide shipping losses to U-boats in August were only 15 ships of 87,000 gross tons as the U-boats sank six ships in the Indian Ocean and five in the Mediterranean.

The average number of U-boats at sea in the Atlantic during August declined to about 60, and most of them were homeward bound by the end of the month. There was no doubt that, as a direct consequence of the loss of a number of supply U-boats and also of the heavy losses suffered by U-boats in the operating areas, the campaigns in the Caribbean and Brazilian Areas were curtailed, and the U-boats returned to base about two weeks earlier than they would otherwise have done.

The number of U-boats sunk during August continued to be satisfactory, considering the smaller number of targets available and the more cautious tactics adopted by the U-boats. Aircraft attacks accounted for 18 of the 25 U-boats sunk throughout the world. Aircraft from the USS *Card* turned in a particularly notable performance by sinking five U-boats during the month. New evidence of the gradual disappearance of all soft spots was indicated by the sinking of three U-boats in the Caribbean-Brazilian Area and two U-boats in the Freetown Area. One U-boat was also sunk in the Indian Ocean, the first in 1943.

As the lull in U-boat activity continued during August and the first three weeks of September, the Allies attempted to maintain the initiative by carrying the battle into the Biscay transit areas. Escort groups were moved closer to the Spanish Coast in an effort to sever the new U-boat routes. However, Germany reacted strongly to this new threat, bringing out a new weapon, the radio controlled, jet propelled glider bomb. These were released by German bombers against the escort groups in the Bay. HMS *Egret* was sunk by this new weapon late in August and two other ships were damaged. The escort groups were withdrawn from the Bay offensive in September, as a result of these attacks and renewed U-boat activity in the North Atlantic.

This resumption of the battle against the vital North Atlantic convoys marked the second attempt of the U-boats to regain the initiative. It was on September 19, 1943, that it first became evident that Convoys ONS 18 and ON 202 were being shadowed by U-boats. That night, attacks developed against both convoys, but the escorts of ONS 18 were able to drive the U-boats off without suffering any losses.

Convoy ON 202 was attacked later that night and HMS *Lagan* was torpedoed. This was the first ship torpedoed in the Atlantic in September. It was also the first indication that the U-boats were using a new weapon, the acoustic homing torpedo (Gnat or T-5). HMS *Lagan* had been detached to follow up an HF/DF bearing and had obtained a radar contact which faded when the range was about 3000 yards. She was within about 1200 yards of the assumed diving position when she was hit by a torpedo which blew off her stern. She was taken in tow and reached harbor. In the morning two merchant ships of Convoy ON 202 were also torpedoed.

During the forenoon the two convoys were ordered to join, forming one convoy of 63 ships and about 15 escorts. That evening two escorts were sunk, one while hunting a U-boat, the other while following up a radar contact. Despite these losses, the attempts which the U-boats made on the convoy during the night failed. Early on the 21st, the convoy was rerouted to the southward in order to get within range of Newfoundland based aircraft. However, heavy fog prevented much air cover that day and also hampered the U-boats. The U-boats, estimated to be 15 or 20 in number, had the worst of it that night. Thanks to HF/DF fixes by the escorts, the U-boats were prevented from sinking any ships and in the early hours of the 22nd, one of the pack was rammed and sent to the bottom by HMS *Keppel*.

Liberators gave cover throughout the day but the convoy was rather opened up by night and the U-boats again attacked in strength. Just before midnight one escort was sunk, later three merchant vessels were torpedoed and one more ship was sunk early that morning. The U-boats kept in contact with the convoy during the 23rd, but the attacks made by escorting Liberators from Newfoundland so deterred

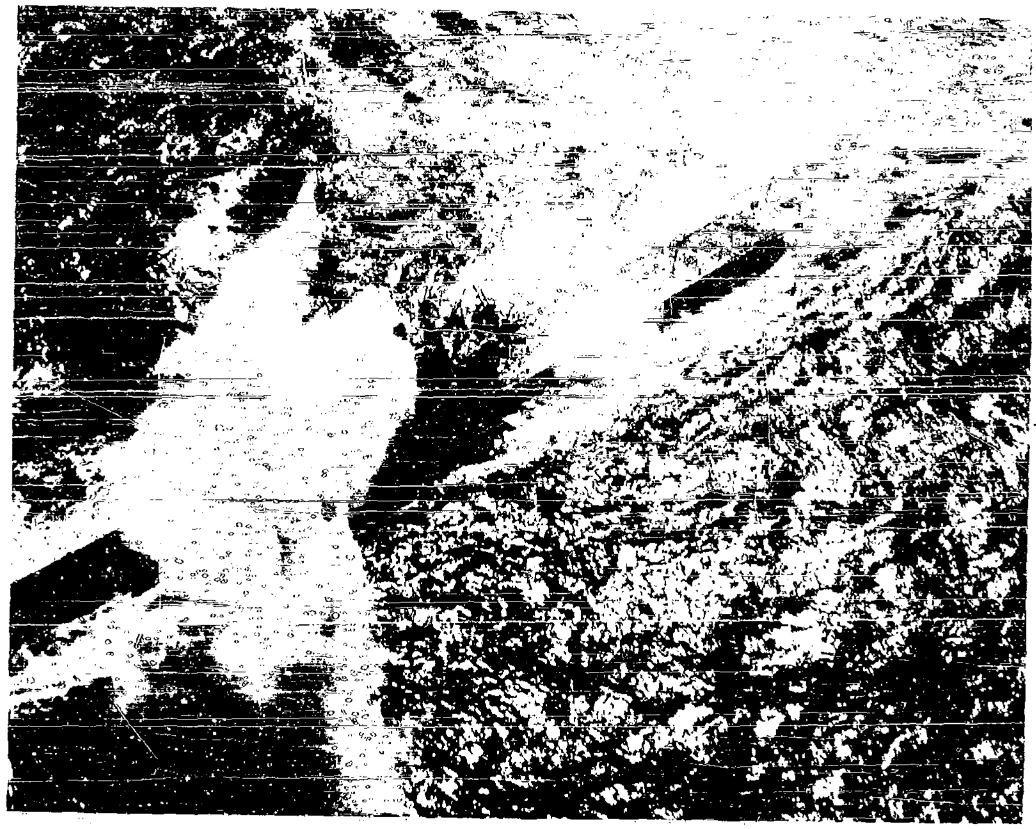


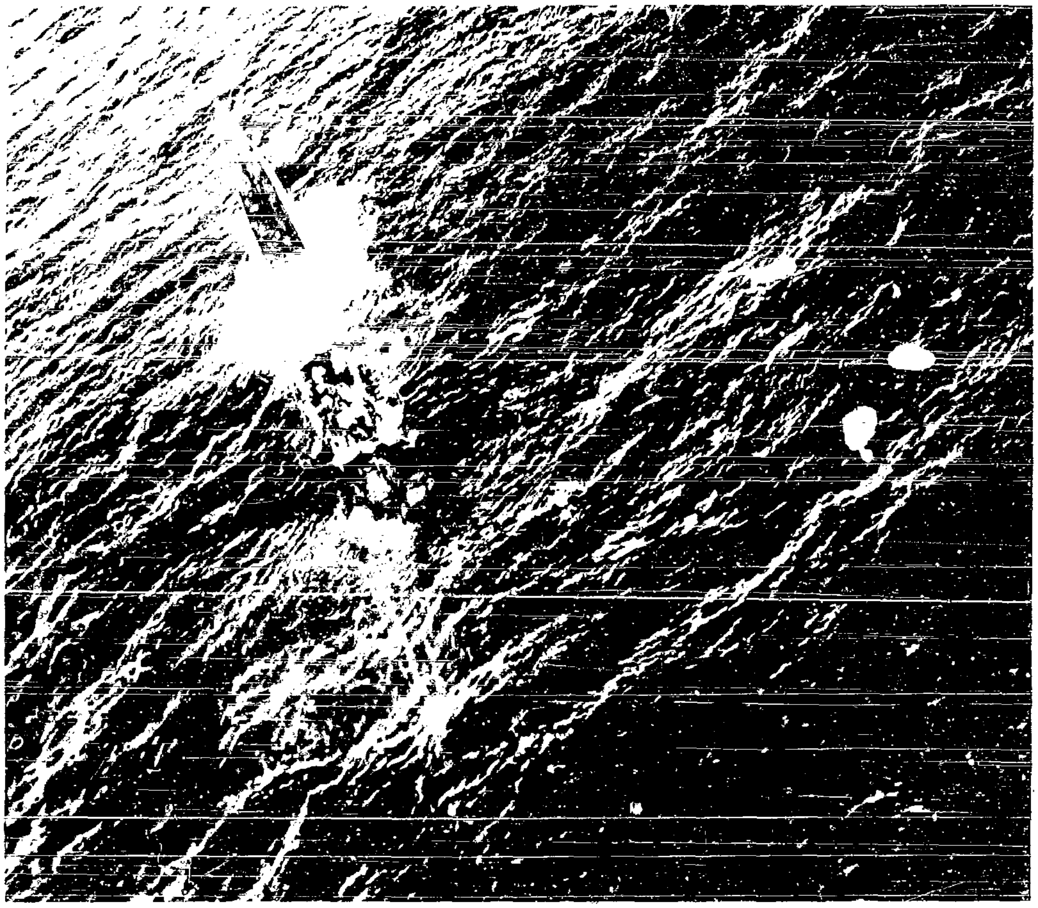
FIGURE 1. Bomb explodes close aboard in attack by aircraft from USS C[illegible] August [illegible], 1943 off the Azores. Note anti-[illegible]

claim that their attacks that night were halfhearted and they lost contact with the convoy next day.

In all, six merchant vessels and three escorts had been sunk and another escort damaged. Three U-boats were sunk, two by covering aircraft and one by an escort. Although heavy losses were inflicted on the escorts by the acoustic torpedo, on only three occasions did U-boats succeed in firing torpedoes at the convoy. The U-boats were more reluctant than ever to press home their attacks, and as soon as they were detected, they made every effort to escape, either at high speed on the surface or by going deep. HF/DF was again of great value in determining the direction of impending attacks.

The actual results of this battle would probably have proved disappointing to the enemy but captured documents indicate that the U-boats greatly overestimated the damage inflicted by the acoustic torpedoes. In addition, they felt that the heavy fog was largely responsible for saving the convoy from much heavier losses. This probably accounts for the greatly increased effort they made against the North Atlantic convoys in October 1943.

The world-wide shipping losses to U-boats in September were 20 ships of 119,000 gross tons, only slightly higher than the August losses. In addition to the six ships sunk in the North Atlantic, two were sunk in the Brazilian Area, six in the Mediterranean and six in the Indian Ocean. About five German U-boats appeared to be responsible for the sinkings in the Indian Ocean and there was evidence that they were using Penang as a temporary base. The more cautious tactics of maximum submergence served to reduce the number of U-boats sunk during



[illegible] USS C[illegible] August 9, 1943. U-boat is [illegible]

September to only 40. By the end of September 1943, however, the Italian Fleet had surrendered, and 29 Italian U-boats had come under Allied control.

Encouraged by their supposed successes in September, the U-boats increased their attack against the North Atlantic convoys. The downward trend in the number of U-boats at sea was reversed, and there were about [illegible] U-boats at sea in the Atlantic in October as compared to only about 50 in September. Over 40 U-boats were concentrated in the Northwest and Northeast Atlantic Areas and the days of wolf pack attacks on convoys seemed to have returned.

However, this time the U-boats suffered a much more decisive defeat than the one they had experienced in May 1943. First of all, the U-boats had trouble in locating Allied convoys because of evasive routing, and they were able to inflict losses on only three of the North Atlantic convoys during October. Then again, the U-boats were not attacking with the same aggressiveness they had shown in the past, and they were able to sink only three merchant vessels and one escort. Moreover, the U-boats had to pay the prohibitive price of over seven U-boats sunk for each merchant vessel sunk as 22 U-boats were sunk during October in the Northwest and Northeast Atlantic Areas. Aircraft played a major part in this decisive setback of the U-boats destroying 17 of the 22 U-boats sunk in these areas. Carrier based aircraft accounted

for six of these 17 U-boats with four of the kills due to aircraft from the USS *Card*. In two cruises, aircraft from the USS *Card* had made 19 attacks, nine of which resulted in A or B assessments. This second cruise closed with the gallant action in which the USS *Borie*, one of the escorts of the USS *Card*, was lost.

On the night of October 31, after having severely damaged one U-boat reported by a plane from the USS *Card*, the USS *Borie* made radar contact with another U-boat. Sonar contact was obtained and a depth-charge attack brought the U-boat to the surface. The U-boat tried to escape on the surface, but the *Borie* opened fire and then rammed the U-boat at 25 knots, riding over the U-boat's forecastle and pinning it under. The two ships remained in this position for about 10 minutes with the U-boat exposed to fire from the *Borie's* 4-inch and 20-mm guns, Tommy guns, revolvers, rifles, and shotguns. One of the U-boat's crew was killed by a sheath knife thrown from the *Borie's* deck while another was knocked overboard by an empty 4-inch shell case. At length, the U-boat got under way, with the Borie, now severely damaged, in full pursuit maintaining gunfire. A torpedo was fired at the U-boat but missed. The range was then closed again and, as the attempt to ram failed, three depth charges were fired straddling the U-boat. Another torpedo was then fired passing within 10 feet of the U-boat's bow. A main battery salvo struck the U-boat's diesel exhaust and the U-boat immediately slowed, stopped, and surrendered. About 15 members of the crew abandoned ship and the U-boat sank stern first. The entire action from the initial contact until the U-boat sank lasted one hour and four minutes. Unfortunately, the ramming resulted in serious damage to the *Borie* and she had to be abandoned later in the day.

The world-wide shipping losses to U-boats in October were about the same as in September. Only 20 ships of 97,000 gross tons were sunk, but the number of U-boats sunk increased to 27 reflecting the increased U-boat activity. The U-boats were forced to disengage again in their battle against the North Atlantic convoys and their second attempt at a come-back had failed. The first promising results of the acoustic torpedo were not maintained, and during October this new weapon had singularly little success. By way of countermeasures the Allies developed a towed noise-making device (U. S. FXR--British FOXER) and new step-aside tactics in attacking U-boats. By the end of October the British had been granted the use of the Azores by Portugal, and air bases were immediately established greatly extending Allied air coverage of the Atlantic.

A fundamental change in U-boat tactics was observed in November 1943 as the U-boats made their third, and most feeble, attempt to regain the initiative. As a result of the heavy losses inflicted on the U-boats by aircraft in October, and also influenced by the Allied air bases on the Azores, the U-boats were compelled to adopt a mode of existence which favored their survival rather than the most effective employment against shipping. In order to favor their chances of survival, the U-boats remained completely submerged during the daytime, thereby avoiding Allied air patrols. They surfaced at night to charge batteries and to follow-up and attack any convoys within reach. Small groups of U-boats were disposed along the probable course of the convoy, about one day's run apart, so that each pack would be able to attack the convoy for only one night. To compensate for this loss of mobility of the U-boats, enemy long-range reconnaissance aircraft were used to locate our convoys and to pass on information to the U-boats.

As most of the enemy's long-range aircraft were based in France, these new U-boat tactics were tried out on the convoy route between the United Kingdom and Gibraltar. Four north-bound convoys were attacked by the U-boats with very little success, as only one ship was sunk while several U-boats were destroyed. Fortunately, the attacks on these convoys came after Allied aircraft had moved into the Azores and strong support by both escort groups and shore-based aircraft brought the convoys safely through the concentrations of U-boats. These attacks also provided Azores-based aircraft with their first kill as a Flying Fortress sank a U-boat at daybreak on November 9.

After the failure of this third attempt at staging a come-back the U-boats reconciled themselves to remaining on the defensive for the remainder of this period. The world-wide shipping losses to U-boats dropped to their lowest level since Pearl Harbor as only 13 ships of 67,000 gross tons were sunk during November 1943. There was a spurt of activity in the Panama Sea Frontier as three ships and one schooner were sunk by U-boats. Not a single ship was sunk in the North Atlantic Convoy Area during the month, while four ships were sunk in the Indian Ocean and three in the Mediterranean. German aircraft, mak-

ing extensive use of torpedoes and glider bombs, had become a greater menace to the Mediterranean convoys than were the U-boats. Aircraft sank seven ships of over 60,000 gross tons in the Mediterranean during November, six of them off the coast of North Africa between Iran and Bizerte. Early in the month, the enemy's attempt to reinforce the diminishing number of U-boats in the Mediterranean was largely frustrated as three of the five U-boats making the attempted entry were sunk.

In all, 18 U-boats were sunk during November, about half by aircraft and half by surface craft. These U-boat kills were rather widely distributed. The Second Escort Group sank two U-boats using a creeping attack. This method of attack was developed to take care of deep U-boats and involved one ship's keeping contact with the deep U-boat at a distance and directing the attacking ship onto the unsuspecting U-boat. The attacking ship proceeded silently at slow speed in order to surprise the U-boat before it could start any violent evasive maneuvers. When the attacking ship was over the U-boat, it would drop a large pattern of depth charges.

Two large U-boats, apparently headed for the Indian Ocean, were sunk in the South Atlantic during November by U. S. aircraft based on Ascension Island. These sinkings were particularly valuable as the Indian Ocean was one of the few remaining areas where the exchange rate was still favorable to the U-boats. The sinking of a U-boat headed for the Indian Ocean might be considered equivalent to the saving of ten ships, which the average U-boat would probably sink in the Indian Ocean before it itself would be sunk.

Barrier patrols by aircraft in the South Atlantic paid off during the last week of December 1943 and the first week of January 1944. Five enemy merchant vessels attempted to return from Japan to Germany and were in the South Atlantic heading north. One of the five enemy blockade runners made port, badly damaged; three were sunk by ships and aircraft of the Fourth Fleet in the Brazilian Area, and another was sunk by British-based aircraft in the approaches to the Bay of Biscay. This was the last attempt the enemy made to run the blockade with merchant vessels, but U-boats continued to make occasional trips between Germany and Japan.

World-wide shipping losses to U-boats stayed at the same low level as only 13 ships of 87,000 gross tons were sunk by U-boats in December 1943. Although over half of the 60 U-boats at sea in the Atlantic were concentrated in the North Atlantic Convoy Area, not a single ship was sunk there. All the sinkings were due to small numbers of U-boats operating in distant areas. Five ships were sunk in the Indian Ocean, three in the Freetown Area, and one in the Mediterranean. The other four ships were sunk in American coastal waters extending from Cape Hatteras to Aruba. However, the U-boats' policy of remaining submerged during the daytime resulted in only seven U-boats being sunk during December, the lowest monthly total in 1943.

The shipping losses to U-boats in December were overshadowed by the surprise air attack on Bari Harbor, on the east coast of Italy, on December 2. This attack, made by about 25 bombers, resulted in the loss of 16 ships and damage to 10 others. The heavy losses were due in part to the explosion of several ammunition ships.

The U-boats sank only 13 ships of 92,000 gross tons in January 1944. Two of these ships were sunk from North Atlantic convoys. Three ships were sunk in the Barents Sea Area from a convoy headed for Russia while eight ships were sunk in the Indian Ocean. The main concentration of about 25 U-boats in the North Atlantic moved gradually eastwards, towards the west coast of Ireland, in an apparent attempt to locate Allied convoys. This move did not succeed as no ships were sunk in the Northeast Atlantic Area while seven U-boats were destroyed there. However, only 14 U-boats were sunk in January as the U-boats continued their cautious tactics of maximum submergence. Fear of the impending invasion may have played its part in keeping the U-boats within short range of the French coast.

February 1944 marked the fourth successive month in which fewer than 20 ships and less than 100,000 gross tons of shipping were sunk by U-boats. Only 18 ships of 93,000 gross tons were sunk during the month, ten of them in the Indian Ocean, six in the Mediterranean, and only two in the Atlantic, one near Iceland and one in the Freetown Area. About half of the 60 U-boats at sea in the Atlantic were concentrated in the North Atlantic, west of the United Kingdom. However, the North Atlantic convoys passed through this concentration of U-boats without suffering any losses while severe losses were inflicted on the U-boats. The world-wide total of U-boats sunk mounted to 22 in February, as ten were destroyed in the Northeast Atlantic Area.

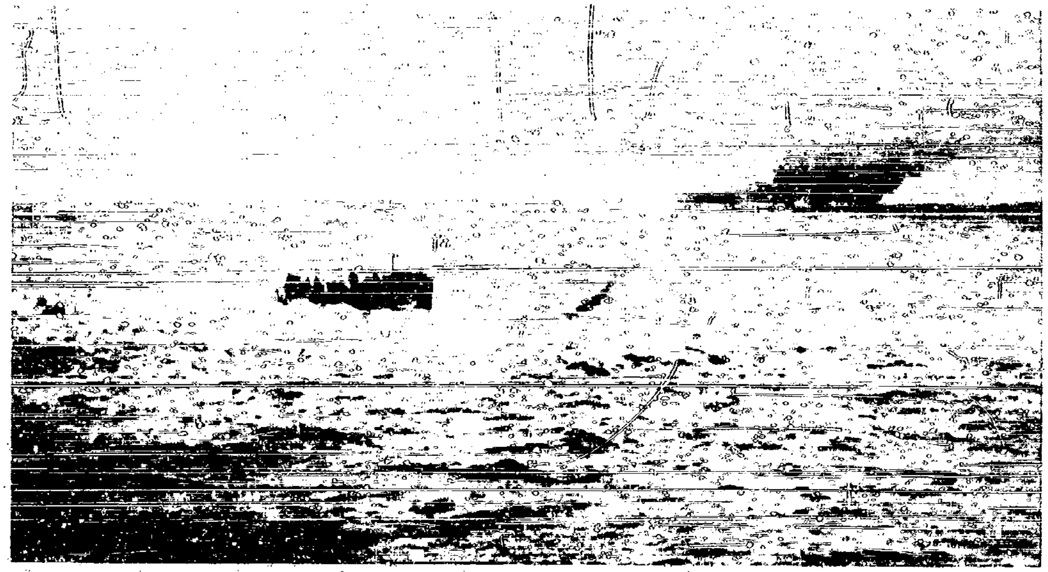


FIGURE 3. Crew of U-550 prepare to abandon ship after attack by USS *Joyce*, *Gandy*, and *Peterson*, 200 miles off New York, April 16, 1944. SS *Pan Pennsylvania* burning in the background.

The outstanding achievement of the month was the 27-day patrol of the Second Escort Group, in the course of which six U-boats were sunk in a period of 20 days. Every U-boat contacted was hunted to destruction. Four hours and 106 depth charges were required, on the average, to kill each of these six U-boats. Combined creeping and follow-up attacks were responsible for the destruction of four of them. Against these successes must be recorded the loss of HMS *Woodpecker* to an acoustic torpedo. In contrast to these attacks, HMS *Spey*, fitted with the latest type of Asdic gear including the Q attachment and the Type 147B depth predictor, destroyed two U-boats in two days, each in a matter of minutes. Single patterns of ten depth charges forced the U-boat to the surface in each case.

Another outstanding feature of the month's operations was the first sinking of a U-boat as the result of an initial MAD contact. U-boats had, during the previous months, approached on the surface at night and passed through the Straits of Gibraltar in the daytime entirely submerged. They made only enough speed to maintain trim, while the current carried them through. Allied ships, operating in the Straits, faced bad sound conditions, because of the variation in the density of the water. Echo ranging was unreliable and listening was not of much value either, as the U-boats proceeded at very slow speeds.

This situation presented an ideal set-up for the use of MAD. An MAD barrier patrol was started across the Straits in January 1944, in order to prevent the submerged passage of U-boats into the Mediterranean. Two PBY's of VP63 were flying on this patrol on February 24 when an MAD contact was obtained. Shortly afterward, two British destroyers and other planes arrived on the scene. The U-boat was attacked with retro-bombs from the MAD planes, depth charges and gunfire from the destroyers, and depth bombs from the other aircraft before it was destroyed. This MAD barrier patrol probably destroyed another U-boat attempting to make the passage in March.

During March 1944 there were some signs of the breaking up of the concentrations of U-boats in favor of a general dispersion across the North Atlantic convoy lanes. There was an increase in the shipping losses to U-boats as 23 ships of 143,000 gross tons were sunk throughout the world. Losses were again heaviest in the Indian Ocean where 11 ships were sunk, but the German U-boats operating there were seriously inconvenienced by the sinking in the South Indian Ocean of two tankers which had been refuel-

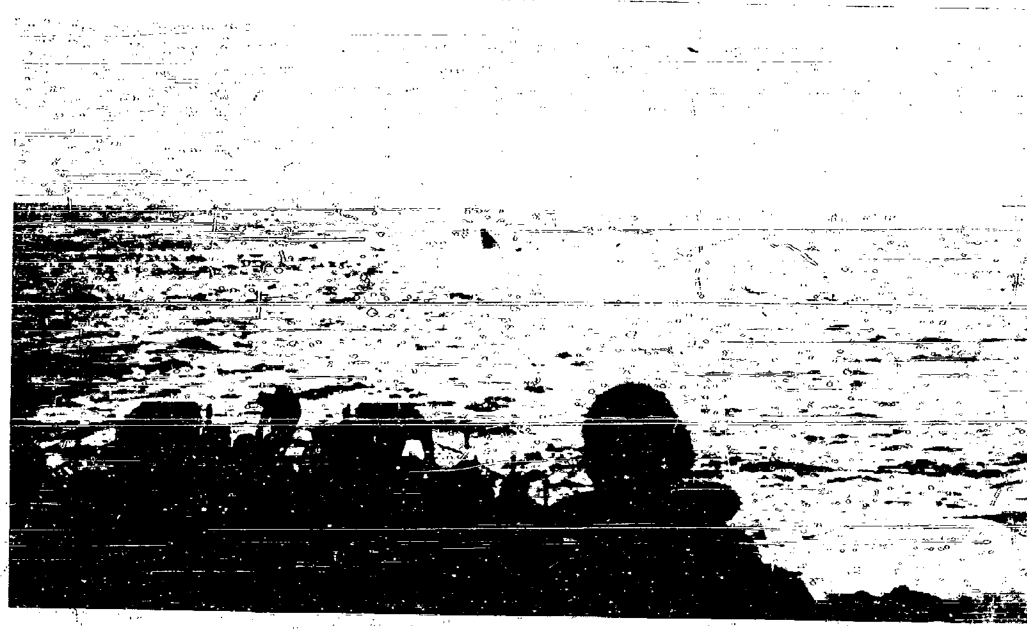


FIGURE 1. U-550 sinks.

ing them. No ships were sunk in the Indian Ocean during the remaining two months of this period. Seven ships were sunk in widely scattered parts of the Atlantic in March, four in the Mediterranean, and one in the Barents Sea Area.

The number of U-boats sunk increased for the third successive month as 23 U-boats were destroyed in March, the same as the number of ships sunk by U-boats. Two of the longest U-boat hunts of the war occurred at about this time; one lasting 30 hours and the other 38 hours before the U-boats were destroyed. The Second Escort Group accounted for two more U-boats in March, bringing its total up to 11. One of these was sunk with the cooperation of aircraft from the escort carrier, HMS *Vindex*.

The escort carrier groups contributed greatly to the campaign in March, sinking nine U-boats in the Atlantic. Aircraft from HMS *Chaser*, using rockets, participated in the sinking of three U-boats. Aircraft and escorts of the USS *Bogue* participated in the sinking of one U-boat while two other U-boats were sunk by escorts of the USS *Block Island*. Toward the latter part of the month, the USS *Block Island* task group, operating in a probable refueling area near the Cape Verde Islands, sank two more U-boats. Sono-buoys were used in this operation.

In the Mediterranean, the enemy lost five U-boats out of the comparatively small number remaining there. Two of these were sunk in a raid by U. S. Army Liberators on the U-boat base at Toulon. The lack of sightings in the Bay of Biscay caused Coastal Command to send its aircraft closer to the French coast and a U-boat was probably sunk by hits from 6-pounder gunfire from a Mosquito. A Catalina from Capetown sank a U-boat about 400 miles south of the Cape of Good Hope.

The average number of U-boats at sea in the Atlantic dropped to 50 in April 1944 as the enemy continued to conserve his U-boats in anticipation of a major effort against the threatened invasion. U-boat patrol dispositions were rather sparse and wide-flung and great importance seemed to be attached to the gathering of meteorological information, in aid of military and air planning. Only nine ships of 62,000 gross tons were sunk by U-boats during the month, seven in the Atlantic and two in the Mediterranean.

For the first time in 14 months, not a single ship was sunk by U-boats in the Indian Ocean. However, the most disastrous event of the month occurred there, when on April 14 an ammunition ship exploded in Bombay harbor, completely destroying 14 ships and damaging nine others. As partial com-

pensation for this disaster, the world-wide losses due to enemy action reached a new low for the war as only 13 ships of 82,000 gross tons were sunk in April.

Starting in April, the U. S. ocean escorts of the UGS convoys continued past Gibraltar into the Mediterranean as far as Bizerte before being relieved by British escorts. Each of these three April convoys was subjected to the familiar Nazi air attack near Algiers as a result of which three ships were sunk and five damaged.

On the night of April 20, the Germans made an unsuccessful attack with human torpedoes at Anzio, and both prisoners and craft were taken. These craft consisted of two torpedoes, one mounted about 6 inches above the other. The "mother" (upper) torpedo was modified to hold a human pilot who guided the craft and released the normal lethal torpedo attached underneath when within firing range.

Considering the inactivity of the U-boats, it was remarkable that 16 of them were sunk during April. The escort carrier groups accounted for six of these.

The average number of U-boats at sea in the Atlantic declined to only about 40 in May 1944. However, a large number of U-boats, which normally would have been operating in the Atlantic, was apparently being held in Biscay ports and in Baltic and Norwegian ports for use against the forthcoming invasions. World-wide shipping losses to U-boats were lower than they had ever been before as only four ships of 24,000 gross tons were sunk by U-boats during May. Three of these ships were sunk in the Brazilian Area and one in the Mediterranean. Total shipping losses from all causes also dropped to a new low as only 12 ships of 40,000 gross tons were lost during May.

The most notable achievement of the U-boats during May was the sinking of the escort carrier, USS *Block Island*. Early in the month one of her planes assisted while the USS *Buckley*, one of her escorts, finished off a German U-boat after a short (16 minutes) but thrilling surface engagement involving gunfire and ramming. On May 29, while the task group was searching for a U-boat suspected to be in the vicinity, the *Block Island* was struck by three torpedoes in a short interval. One of the escorts had her stern blown off. Shortly thereafter, the other escorts made contact with the U-boat and probably sank her after two Hedgehog attacks. The gallant career of the *Block Island* came to an end later in the day when she had to be abandoned.

Despite the enemy's attempt to conserve his U-boats for the imminent invasion, the number of U-boats sunk during May 1944 was 29, the highest figure since the record total of 46 in July 1943. The leading area in the sinking of U-boats during May was the Northern Transit Area, East, where ten U-boats were destroyed during the month, nine of them by aircraft. Three of these were sunk by aircraft from HMS *Fencer* which was escorting a convoy from Russia in the early days of the month. During the latter part of May, a considerable increase was noted in the number of Baltic U-boats en route to the Atlantic via the Iceland-Faroes passage. For some time past the operations of Allied submarines against enemy shipping in Norwegian waters had prevented aircraft from making sweeps in this area. The enemy may have thought that he could safely relax his precautions in this area as many of these U-boats were traveling on the surface. Coastal Command aircraft quickly exploited this soft spot, sinking six U-boats during the latter part of the month.

The small number of U-boats in the Mediterranean was further depleted as four U-boats were destroyed there in May while another was sunk while attempting to pass through the Straits of Gibraltar. This was the third successful attack on a U-boat as a result of an initial MAD contact. The four successful attacks in the Mediterranean demonstrated the importance of persistence and the value of close cooperation between air and surface units. Three of the four hunts involved aircraft as well as surface craft and the durations of the actions ranged from 22 hours to 76 hours. This record action, which began on May 14, was culminated on the 17th with the sinking of a U-boat after a continuous hunt of 76 hours involving eight ships and three planes. The U-boats in the Mediterranean fought back strenuously, sinking one merchant vessel and two escorts and damaging four other ships during the month.

The outstanding event of the month, and probably the outstanding achievement of the U-boat war by a single ship, was the performance of the destroyer escort, USS *England*, in the Pacific from May 19, 1944 to May 31. During this brief period, the USS *England* destroyed five Japanese U-boats and was assigned the major credit in the destruction of a sixth U-boat. The Hedgehog was the primary weapon used in achieving these results. This series of attacks resulted from the suspicion that a force of about five Japanese U-boats was patrolling the line of the Equator, to the

northeast of the Admiralty Islands. The USS *England* was accompanied by USS *George* and *Raby* when they swept through this area. The outstanding performance of the *England* is the more remarkable in that it was her first contact with the enemy.

There was some credible evidence from aircraft sightings and attacks in the final week of May 1944 that two or more U-boats were at sea in the Western English Channel, off the French coast. This proved to be a preview of the nature of U-boat operations in the next period as, for the first time since the early days of the war, the U-boats returned to the hazardous shallow coastal waters in the vicinity of England. This operation was possible only because the U-boats could take advantage of the use of Schnorchel and thereby reduce their exposure to aircraft attacks.

6.2 COUNTERMEASURES TO THE U-BOAT

6.2.1 Convoys

During this period, the U-boats tried several modifications of their previous wolf-pack tactics in an effort to gain the upper hand in their attacks on Allied convoys.

The first modification in tactics was made in September 1943 in the attacks on the North Atlantic convoys. It was based on the use of the acoustic torpedo and involved attacking the escorts first, with the objective of reducing the convoy defenses to a point where the merchant vessels would become easy prey for the U-boats. Although some escort vessels were sunk, the objective was never accomplished; because at this stage of the war the Allies were using a larger number of escorts with the convoys and had a sufficiently large number of antisubmarine ships available that the loss of a few escorts would not seriously handicap future convoys. These U-boat tactics might have proved more effective in the early days of the war when the number of antisubmarine ships available to the Allies was extremely limited.

The second modification was made in November 1943 in the attacks on the convoys between Gibraltar and the United Kingdom. This change in tactics was forced on the U-boats by the heavy Allied air coverage of the North Atlantic which prevented the U-boats from operating on the surface in the daytime and thereby prevented the concentration of a large number of U-boats around a convoy. The tactics adopted by the enemy involved stationing small packs of U-boats along the path of the convoy. Long-range aircraft from Bordeaux were used to shadow Allied convoys during the day. Reports of the air reconnaissance were passed on to the U-boat packs, which then attempted to maneuver into a favorable position for a night attack. This change in tactics came a little late, too, since flying facilities had become available in the Azores in October 1943. Several convoys were intercepted by the U-boats, but strong support by escort groups and land-based aircraft brought the convoys safely through with only negligible damage.

The third modification in U-boat tactics, made after the setback in November 1943, involved the almost complete abandonment of the old, highly organized wolf-pack attacks. Concentrations of U-boats were still maintained in the North Atlantic but attacks were generally made by individual U-boats who happened to find themselves in a favorable position to attack a convoy. Although these U-boat tactics were much less effective against Allied shipping, they did enable the U-boats to remain submerged during the daytime. The scarcity of supply U-boats may have also been a factor in this drastic modification of wolf-pack tactics, which had been predicated on high-speed surface operations of the U-boats, requiring high fuel consumption.

These futile attempts by the U-boats had very little success. Only about six ships a month were sunk by U-boats from Allied convoys. The tonnage sunk from convoys by the U-boats was only about 10 per cent of the total tonnage sunk by them. The degree of safety reached by convoyed shipping during this period is well illustrated by the experiences of the North Atlantic trade convoys (HX, SC, ON, ONS). Of the 900 ships that sailed monthly in these convoys, only about 1½ were sunk each month by U-boats. This represented a loss rate of only about one sinking per 600 transatlantic trips. This high degree of safety from U-boats was typical of the other convoy systems as well.

One of the primary reasons for the ineffectiveness of the U-boats against Allied convoys was poor U-boat morale, as evidenced by their failure to press home attacks on convoys once they were detected. It is not difficult to see the reasons for this lack of aggressiveness. In the early months of 1943, Allied bombers had reduced the Biscay ports to heaps of stones. Though they could not get at the U-boats in their shelters, these raids deprived the U-boat crews

of all but the most primitive facilities after they had come back, through continually mined waters, from long, exhaustive, dangerous, and now unsuccessful patrols. To reach the North Atlantic, the U-boats had to proceed submerged through the Bay of Biscay for the first five or six days of their patrol, surfacing for only a few hours after midnight. To find the convoy, the U-boats had to pass through the areas remorselessly swept by covering aircraft, and when the U-boats sighted the convoys, they found more numerous and better equipped escorts manned by more highly trained crews.

An analysis of attacks on shipping by U-boats, indicating some of the factors governing the safety of ships against U-boat attacks, was made during this period and had considerable influence on Allied measures for the protection of shipping. This study indicated that the safety of independent ships depended very much on the speed of the ship, with the 12-to-14 knot region being critical. A 12-knot ship had about three times the probability of being sunk as a 14-knot ship making the same trip. The explanation of this appears to be that the U-boat cannot, in general, follow a ship of 14 knots or above for any length of time and if it is not in a suitable position to make a submerged attack immediately, the ship will escape. The U-boat can follow slower ships on the surface, at a suitable distance, working round to a position from which it can attack on the surface at night.

Speed was a significant factor in the safety of convoyed shipping only when air escort was present. This study showed that the 9-knot convoys were considerably safer than the 7-knot convoys when air cover was available. When there was no air escort, the U-boat could proceed towards the convoy at high surface speeds and the extra 2 knots did little to prevent the U-boat from overhauling it. Another striking result which emerged from this analysis was that the number of ships sunk was roughly independent of the size of the convoy as long as the number of escorts was the same. This meant that large convoys would lose, on the average, a smaller percentage of ships to U-boat attack and they would also be more economical in the use of escorts.

The average size of the North Atlantic trade convoys increased gradually during this period, rising from about 46 in March 1943 to about 57 in March 1944. In April 1944 certain changes were made in the North Atlantic convoy schedules in order to allow several escort groups to be withdrawn from convoy duty for use in the invasion. The HX and ON convoy speeds were changed from 10 knots to 8, 9, and 10 knots in rotation, with the suffix S, N, and F designating these respective speeds, while the slow SC and ONS convoys were abolished. The average sailing interval between convoys stayed at 7½ days so that only four convoys sailed each way monthly, instead of six. This produced a substantial increase in the average size of these convoys. The average size of these convoys was 98 in May 1944 and HXM 292, consisting of 135 ships and six escorts, was the largest convoy of the war to that date.

The danger from U-boat attack in the Western Atlantic was so low during most of this period that it was possible to allow some shipping from the U. S. coastal convoys to sail independently whenever a lull in U-boat activity occurred. The program was kept flexible in order to maintain a balance between the increased safety of convoyed shipping and the loss of time due to ships waiting in ports for convoys and sailing at slower convoy speeds. Fast merchant vessels (generally 11 knots and over), with the exception of those carrying high priority cargo, were able to sail independently along the coast during much of this period. Whenever the danger of a U-boat attack appeared imminent, independent shipping was ordered into port to await the next convoy. In some cases, where safety permitted, entire convoys were dispersed and the ships proceeded alone to their destination.

6.2.3 Aircraft

The battle between U-boats and aircraft reached its climax at the beginning of this period, in July 1943. The U-boats, equipped with improved antiaircraft armament in the form of the quadruple 20-mm gun, were traveling on the surface during the daytime and were fighting back against aircraft. They also traveled through the Bay of Biscay in groups for mutual protection.

As a result of their disastrous experience in July 1943 when 34 U-boats were sunk in the Atlantic by aircraft, the U-boats were forced to abandon these aggressive tactics. The enemy realized that the U-boats were beaten and decided upon more cautious tactics that favored self-preservation of the U-boat fleet until new technical equipment and modified U-boats could turn the tide. These new

tactics involved complete submergence of the U-boats during the daytime. The fact that aircraft had swept the U-boats from the surface during the daylight hours constituted a real triumph for the Allies, as U-boats, robbed of their aggressiveness and mobility, lost a great deal of their effectiveness.

The new tactics first became apparent in August 1943 in the critical Bay of Biscay transit area. The U-boats reverted to surfacing at night for the minimum time necessary for charging batteries. In addition, they made the transit hugging the coast of Spain, where it was rather difficult for the Leigh-Light Wellingtons to patrol because of their limited range.

These changes had a profound effect on the Bay of Biscay campaign, and the productivity of Allied flying was greatly reduced. About 7000 hours were flown monthly in the Bay during the 5-month period from August 1943 through December 1943. These flying hours yielded only 12 sightings, six attacks, and one kill a month. Thus, although the flying effort was greater than during the preceding peak period (February 1943 – July 1943), the results achieved were only one-fifth as great. Only part of this decrease can be explained by the drop in the number of U-boat transits from 100 a month in the previous period to only about 45 a month during this period. The average number of sightings per 1000 hours on patrol dropped to only two and only 25 per cent of the U-boat transits were sighted. The efficiency index (sightings per 1000 flying hours on patrol per 100 U-boat transits) dropped from nine in the previous period to only four.

The U-boats' policy of maximum submergence during the daytime put great pressure on the development of suitable equipment and tactics to enable the air offensive to be maintained during the night. Considerable effort was devoted to the development of searchlights and flares that would improve the low effectiveness of night attacks, and the first attack on a U-boat by a U. S. searchlight-equipped plane was made in December 1943 by a PBM from Trinidad. In addition, squadrons were trained in night operations from escort carriers.

Coastal Command made a great effort to increase the amount of effective night flying in the Bay of Biscay by increasing the number of long-range searchlight-equipped planes. Leigh lights were fitted to Liberators as well as to additional squadrons of Wellingtons. The effectiveness of this increased amount of night flying was counteracted by the U-boats' use of the Naxos GSR, which detected Allied S-band (10-cm) radar. The enemy started fitting his U-boats with this equipment in October 1943. The net effect of these changes was a small increase in the number of sightings in the Bay of Biscay. About 20 sightings and 15 attacks were made monthly in the Bay during the first five months of 1944. However, the effectiveness of Allied flying in the previous peak period was not even approached.

U. S. Navy planes participated in the Bay of Biscay offensive during this period under the operational control of Coastal Command. When the U-boat situation along the East Coast of the United States started easing up in August 1943, the U. S. Army Anti-Submarine Command was withdrawn from antisubmarine operations. The U. S. Army Air Forces squadrons which had been operating in England were relieved by U. S. Navy Liberators. The U. S. Navy planes in England constituted Fleet Air Wing 7.

Carrier-based aircraft emerged as one of the most dangerous enemies of the U-boat during this period. The U. S. escort carriers took the offensive against the U-boat in regions outside the range of shore-based aircraft, especially in possible refueling areas for the U-boats. This offensive was remarkably successful and rendered most of the Atlantic unsafe for surfaced U-boats.

The U. S. escort carrier [CVE] operating with a screen of about four destroyers or destroyer escorts, composed a task group, assigned to antisubmarine warfare in the Atlantic. The primary mission of the task group was to protect convoys while the secondary mission was to search out and destroy the U-boats. These task groups operated with the convoys between the United States and Gibraltar. That the primary mission was accomplished may be seen from the fact that 2200 ships crossed the Atlantic in the GU and UG convoys from May 1943 through December 1943 and only one ship was sunk by U-boat action.

A study of attacks made by U. S. CVE-based aircraft during this period provides some evidence that their secondary mission was also fulfilled. About 28 days were spent in U-boat waters on the average cruise and about 50 plane hours were flown per day. While in U-boat waters, one sighting was made for every 600 flying hours. Sixty of the 68 sightings studied resulted in an attack and about 40 per cent

of the attacks resulted in the sinking of the U-boat. The high quality of these attacks was due in a large part to the ability of the fast CVE-based planes to surprise the U-boat and attack it while it was still on the surface. Another factor in the success of these attacks was the cooperation between the F4F fighter planes, who strafed the U-boat, and the TBF bombers.

The British escort carriers, operating in the very bad weather of the Arctic, played a major role in getting the Russian convoys through. The North Russian convoys were started again about November 1943 after having stopped running in March 1943. The sinking of the *Scharnhorst* was the most publicized part of this battle. The U-boats accomplished much less against these convoys during this period than in the past. During the period from December 1943 through May 1944, the U-boats sank only five merchant vessels and two destroyers from these convoys while 11 U-boats were sunk. British escort carriers played a major role, contributing six of the 11 U-boat kills. In one round trip of 16 days, with only eight days of operational flying, Swordfish planes from HMS *Chaser* sighted 21 U-boats, attacked 15, and with the aid of surface craft sank three of them.

Rocket projectiles were used very successfully by the British carrier-based aircraft during this period. The first rocket attacks by U. S. planes were made in January 1944 by aircraft from the USS *Block Island*. The U-boat was sunk; however, it was difficult to decide whether the sinking was due to the rockets or to depth charges which were also used in the attack.

The lethality of aircraft attacks during this period was more than twice as high as it had been in the previous period. About 25 per cent of the aircraft attacks made on the U-boats in the Atlantic and Mediterranean resulted in the destruction of the U-boat while about 40 per cent of the attacks resulted in at least some damage to it. The effectiveness of aircraft attacks in the first half of 1944 was lower than the peak reached during the last half of 1943 when some U-boats were still staying on the surface and fighting back. This falling off in effectiveness also reflected the U-boats' tactics of maximum submergence during the daytime as a much larger proportion of aircraft attacks, during the first half of 1944, were made at night. The accuracy of night attacks was always much lower than that of day attacks.

6.2.3 Scientific and Technical

The decisive defeat suffered by the U boats during the previous period seemed to have stimulated German scientific and technical progress and a number of radical changes were made in U-boat weapons and equipment during this period.

One of the changes in U-boat weapons involved the replacement of the quadruple 20-mm antiaircraft gun mount by a new rapid-firing 37-mm antiaircraft gun. U-boat torpedoes were equipped with FAT gear for use against convoys. This gear caused the torpedo to describe a zigzag course and thereby increased the probability of a hit. The major change in U-boat weapons was the introduction of the T-5 torpedo, a 21-inch electrically driven acoustic homing torpedo. The speed of the T-5 torpedo was about 25 knots and its range about 6000 yards. This torpedo homed on the noise of the target's propellers and its homing radius on a 15-knot escort was usually over 500 yards.

The Allies immediately introduced countermeasures to the acoustic torpedo. The British twin FOXER (towed parallel-bar noisemakers used to decoy the acoustic torpedo from the ship) was born three months before the first acoustic torpedo attack took place. A complete escort group was fitted with twin FOXERS 17 days after the first attack. U. S. ships were fitted with FXR gear, which was similar to the British equipment but involved only a single noisemaker. Ships towing noisemakers or proceeding at speeds greater than 24 knots or less than 7 knots were considered to be relatively safe from acoustic torpedo attacks. Other ships were instructed to use the step-aside procedure when conducting attacks on U-boats which might fire an acoustic torpedo. This was a special tactical maneuver, involving a radical change in course when the U-boat is approached, designed to remove the escort vessel from the most probable danger area from acoustic torpedoes.

The use of these towed noisemakers was unpopular on many ships due to the inconvenience involved in streaming and recovering the gear, to the reduction in maneuverability, and also to the interference with the sonar equipment. However, the noisemakers were undoubtedly effective against the acoustic torpedo. About 32 escorts and 19 merchant vessels are estimated to have been hit by acoustic torpedoes during the war. Very few of these casualties occurred when either the recommended tactical procedure was used, or the towed noisemakers were working

properly. Although the acoustic torpedo was more likely to score a hit than a normal torpedo, there were many cases of malfunctioning of the delicate mechanisms involved and those torpedoes that did hit were less likely to sink the ship due to the fact that they usually hit in the stern.

The radar battle continued to play a prominent part in the U-boat war during this period. In the summer of 1943, Admiral Doenitz said, "The methods in radio location which the Allies have introduced have conquered the U-boat menace." However, the German High Command did introduce some effective countermeasures in the fields of radio communication and radar detection during this period, mainly because German Intelligence finally became aware of the nature of Allied equipment.

The major German scientific effort was put into the development of a search receiver that could detect Allied radar transmissions. At the beginning of this period the enemy still had no idea as to what had caused the huge increase in sightings and attacks on U-boats. The German search receiver had been improved by the fitting of a drum-shaped aerial (wire-basket) which did not have to be removed when the U-boat dived. A better receiver (Wanz G-1) had been perfected and was being fitted on U-boats. This served to reduce the amount of radiation from the set itself but did not help the U-boat situation at all as it could only detect radiation of wavelengths greater than 120 cm. The Germans then introduced the Borkum receiver, a much less sensitive crystal detector covering the 75- to 300-cm band, which produced no radiation at all.

Serious as were the immediate effects of these errors of judgment for the Germans, they extended far beyond their original limits. They engendered in the minds of U-boat captains a fear lest they should betray their presence, and with this fear a distrust of Admiral Doenitz' technical advisers.

Finally, in September 1943, the U-boat command recognized that 10-cm radar was being used against them. The German Air Force had captured the blind bombing aid, HS, which operated on the 10-cm band, in March 1943 and after a period of six months this information finally filtered through to the German Navy. As the simplest countermeasure, and still under the influence of their fear of radiating, the Germans produced in October 1943 a crystal detector receiver, the Naxos, for the 8- to 12-cm band. The first models were crude portable units mounted on a stick. They were not pressure-tight and had to be passed below before diving. The maximum theoretical ranges on Allied radar sets varied from about 5 to 10 miles, but there was a considerable loss of efficiency under operational conditions.

The introduction of the Naxos search receiver did reduce the number of sightings and attacks on U-boats and the number of disappearing contacts on Allied radar sets increased. However, many U-boats continued to be surprised successfully, due to the low efficiency of the gear, and it was evident to the Germans that they still did not have the final solution to the radar problem. The U-boat command took the step of sending to sea a U-boat fully equipped to investigate every type of Allied radar and carrying one of their best technicians with operational experience. He sailed from St. Nazaire in U-406 on February 5, 1944, and was captured when the U-boat was sunk by HMS *Spey* on February 18. A similarly equipped U-boat suffered the same fate in April 1944. These losses probably set back the German radar countermeasures program considerably.

Since the Allies were well aware of the potential effectiveness of an S-band search receiver, there were frequent false alarms reporting the introduction of a new GSR before any existed. The intelligence about Naxos, the increase in disappearing radar contacts, and the drop in U-boat sightings produced immediate Allied reactions. There were a few cases where S-band radar sets were turned off. Steps were taken to develop attenuators, which caused a slow and steady decrease in transmitted power as the range closed, in order to confuse GSR operators. An interim tactic of a "tilt-beam" approach to reduce signal intensity as the range closed was proposed but this proved rather difficult to carry out in actual practice. In addition, increased pressure was put on the development and fitting of X-band radar (3-cm wavelength).

The general conclusion was that S-band radars should not be turned off, due to their much greater search width as compared to visual search and also to the fact that the Naxos sets were inefficient and sightings and attacks continued to be made on U-boats with GSR. In addition, the very fact that aircraft were causing the U-boats to submerge, thereby blinding and partially immobilizing them, greatly reduced the effectiveness of the U-boats in sinking ships.

The Germans produced a number of other devel-

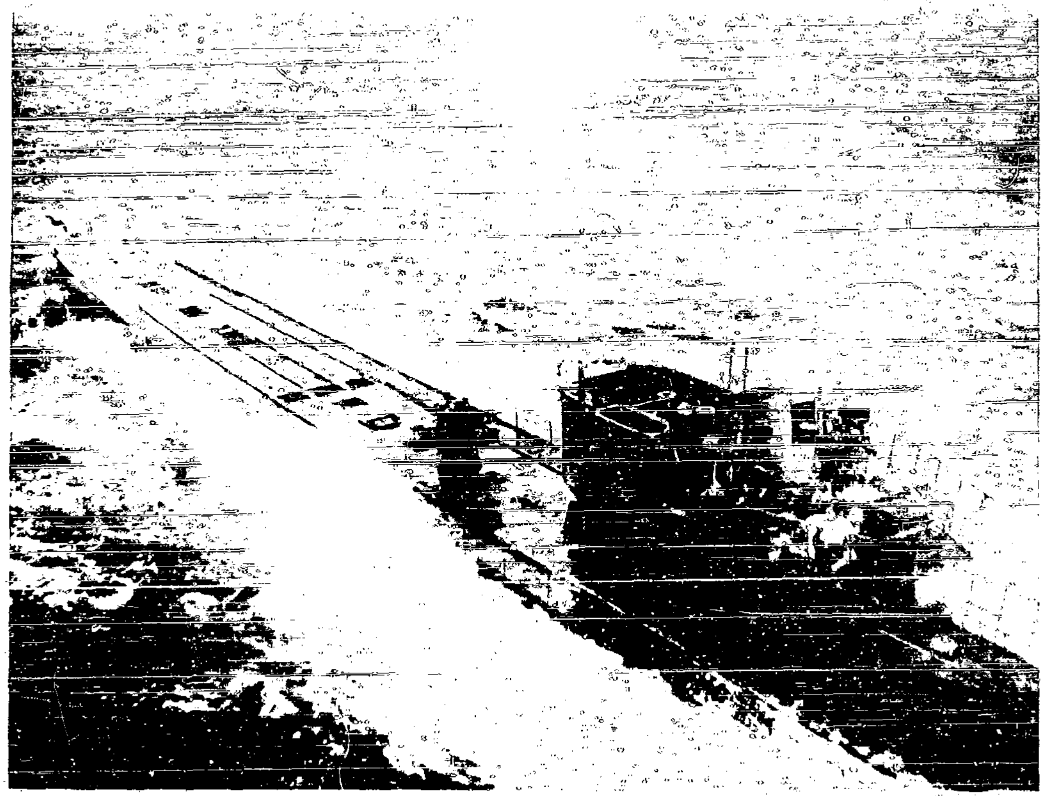
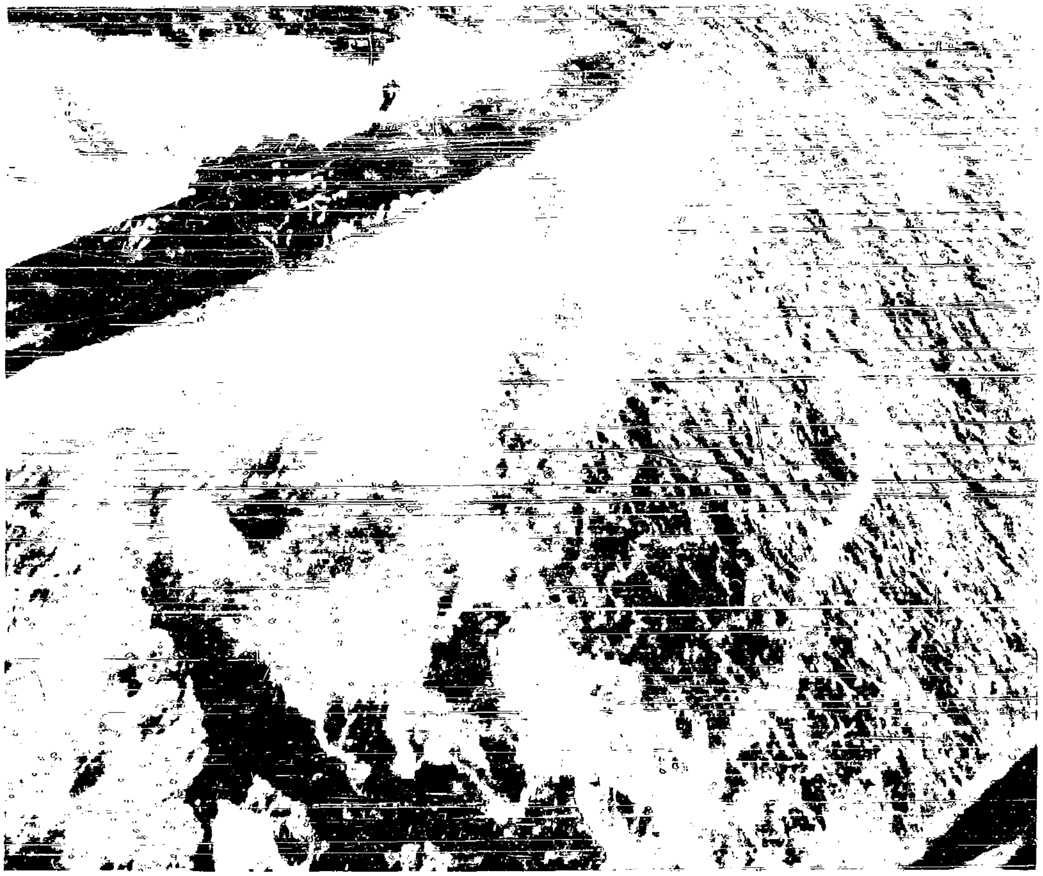


Figure [illegible] U. S. Navy [illegible] VPB-107 [illegible] Ascension Island, November 5, 1943 [illegible]

opments in the radar field. A radar decoy spar, designed to give false radar echoes was introduced but proved ineffective. Some work was done on radar camouflage, with the object of developing rubber coatings for the U-boats that would deflect or absorb radar echoes. Earlier, there had been some attempt to use these rubber coatings against sonar, too. However, the difficulties of producing rubber coatings that would work under operational conditions at sea were very great. The Germans also continued their experiments with infrared searchlights and receivers and took steps to prevent the detection of U-boats by imagined Allied infrared equipment.

During this period, the U-boats finally began to appreciate the danger from Allied shipborne HF/DF as the result of a special Y party going to sea on a specially equipped U-boat. The U-boat command connected their diminishing success to some extent with their communications and tightened them up considerably. The lengths of messages were reduced and the frequencies used were changed more often. These shifts, while they made HF/DF both ashore and afloat more difficult, did not seriously reduce its use or effectiveness. They did make the task of U-boats attacking convoys more difficult.

The most revolutionary technical development of this period was the fitting of Schnorchel to U-boats. The Schnorchel (or snort) is an extensible mast, consisting of an air induction trunk and a diesel exhaust line which are enclosed in a metal fairing. The cross



[illegible]

[illegible] retracted [illegible] until the [illegible] 70 inches. The mast [illegible] about 26 feet [illegible] when raised is a few inches lower than [illegible] of the extended periscope. The Schnorchel [illegible] a U-boat to travel on its diesel engines at periscope depth at speeds of about 6 knots and also to charge its batteries without surfacing. In essence it was a defensive weapon, designed to reduce the amount of time the U-boat had to spend on the surface and consequently to reduce the danger from air attack.

The idea of an extensible air intake, which would enable a U-boat to charge its batteries while submerged, had been current in the German Navy in prewar years but was first brought forcibly to its attention by the capture, in 1940, of two Dutch submarines fitted with such equipment. No steps were taken to follow up this idea while things were going well for the U-boats, and it was not developed until the end of 1943 after aircraft had gained the upper hand over U-boats. The first U-boats were not fitted with Schnorchel until February 1944, and it was not until June 1944, the start of the next phase of the U-boat war, that its effect on U-boat operations became significant.

The U. S. Navy introduced during this period a number of new devices designed to improve the sonar performance of its ships. The Bearing Deviation Indicator (BDI) was one of the most helpful of these sonar aids. BDI was used with standard echo-rang

ing equipment to let the operator see, for every ping, whether the target producing the echo was to the right or left of the bearing of the projector. The operator could, therefore, determine the bearing of the target with greater accuracy and rapidity than with standard echo-ranging equipment alone.

Two new types of depth charges came into use on U. S. ships during this period. The Mark 8 depth charge was fitted with a magnetic proximity fuze which was designed to detonate when within lethal range of the U-boat. The Mark 9 depth charge was steel-cased and shaped so as to have a fast sinking rate, thereby reducing the blind time and consequently the effect of U-boat maneuvers. Both these new depth charges were designed to increase the lethality of surface craft attacks on U-boats.

The British also improved the antisubmarine equipment on their ships during this period, but along different lines than the U. S. Navy. The Squid, which is designed to throw depth charges ahead of the ship and is automatically controlled and operated, came into service at the beginning of 1944. It employs a 3-barreled mortar, electrically fired, designed to dischage bombs ahead of the attacking ship. These bombs closely resemble depth charges in weight and explosive effect but have the following advantages over depth charges:

1. They are projected with accuracy to a known point, well ahead, while the attacking ship is still in Asdic contact with the U-boat.
2. They have a reliable underwater course.
3. They have a much higher sinking speed.
4. They incorporate a new type of fuze which is set automatically to the required depth with a high degree of accuracy.

The depth is set on the fuzes electrically from the new Type 147B Asdic depth predictor. The mortars are fired automatically from the Asdic range recorder. The three charges are thrown to the points of an equilateral triangle. When two mortars are fitted, as in frigates, the pattern is in two depth layers.

The Type 147B Asdic depth predictor was developed primarily for use with the Squid, so as to obtain a measurement of the depth of the U-boat just before the projectiles are fired. However, the Type 174B depth predictor, in conjunction with the appropriate range and bearing recorders and Q attachment, can also be used in Hedgehog and depth-charge attacks. Type 147B uses a fan-shaped beam of high-frequency sound (50 kc) which may be depressed down to 45° below the horizontal. The beam of sound is broad in the horizontal plane (30° to 40° on either bow) and narrow in the vertical plane (2° to 3° off axis). Trials have shown that the set is capable of setting the Squid fuzes to within about 20 feet of the depth of the U-boat, provided it is below 100 feet. At shallower depths it is not possible to get accurate measurements. It is possible to make accurate attacks on U-boats at depths down to some 800 feet, provided that the Q attachment is fitted.

6.2.4 Sinkings of U-boats

The average number of U-boats sunk or probably sunk monthly reached a peak of 21 a month during this period. The record monthly score of the war was reached in the first month, July 1943, when 46 U-boats were destroyed throughout the world. Of the total of 234 U-boats destroyed during this 11 month period, 199 were German, 28 were Japanese, and 7 were Italian. The 180 U-boat sinkings in the Atlantic were rather widely distributed with the leading areas being the Northwest Atlantic Area with 31 kills, the Northeast Atlantic Area with 29 kills, and the Biscay Channel Area with 28 kills.

Aircraft continued to be the leading U-boat killers during this period accounting for 122 alone (52 per cent of the world-wide total) and another 22 (9 per cent of total) with the cooperation of surface craft. Carrier-based aircraft accounted for 40 of the 144 kills in which aircraft participated. Ships accounted for 79 U-boats (34 per cent of total), and Allied submarines accounted for the other 11 U-boats (5 per cent of total).

The quality of surface craft attacks continued to improve steadily through this period as the crews became more experienced and improved weapons and equipment became available. About 30 per cent of the surface craft attacks made on U-boats in the Atlantic and Mediterranean during this period resulted in at least some damage to the U-boat while 20 per cent of the attacks resulted in the sinking of the U-boat. The lethality of these attacks was twice as high as it had been during the previous period. A study of British assessed attacks during this period indicated that about three patterns were dropped in the average attack on a U-boat. The probability of sinking a U-boat was about 6 per cent for the average depth-charge pattern and about 11 per cent for the average Hedgehog pattern.

6.3 SURVEY OF RESULTS

6.3.1 From the U-boats' Point of View

To interpret the results of the U-boat war during this period correctly, it is important to realize that the German High Command appreciated, at the beginning of this period, that the U-boats had been decisively defeated in the crucial battle against the North Atlantic convoys. The enemy also realized that the old type of U-boat would have to be modified radically before it could again be a serious menace to the Allied supply lines across the Atlantic.

The solution reached by the German High Command was the development of an entirely new type of U-boat, more immune from radio location, with much greater submerged speed, and an entirely new and quicker method of production. The first sketch of what was to be the new prefabricated Type XXI U-boat was made in July 1943. By December 1943 all designs were finished, including full-scale wooden mockups. In February 1944 it was decided to stop the construction of the old-type U-boats, except that those that had already been laid down were to be completed, and to concentrate on the production of the new prefabricated U-boats.

The general strategy of the enemy was to keep the U-boat fleet in being until the new U-boats would be ready, when they could return to the offensive again. In line with this policy, the Schnorchel was valuable as an interim measure, to reduce the danger from air attack and to enable the U-boats to operate in inshore waters in the event of invasion. The main aim of the U-boats during this period was self-preservation, although they would attempt in the meantime to sink as much Allied shipping as they could without suffering excessive losses. In addition, keeping the U-boats at sea served to tie up large Allied forces in the protection of shipping, thereby keeping them from being used against Germany in other ways.

During the last half of 1943, the U-boats made several attempts at conducting offensive operations but each time they were beaten back with heavy losses. Thereafter, the U-boats seemed to realize that, if they were to accomplish their primary mission of self-preservation, they could not undertake any large-scale offensives against shipping. The number of U-boats at sea in the Atlantic dropped steadily, reaching a minimum of about 40 in May 1944. The main functions of these U-boats, during the first five months of 1944, were probably reconnaissance, weather reporting, forcing the Allies to convoy shipping, and waiting for the invasion. They made no attempt to sink a large amount of Allied shipping. This is clearly reflected in the results achieved by the U-boats during this period.

World-wide shipping losses to U-boats reached a new low as only about 17 ships of 101,000 gross tons were sunk monthly by U-boats. This was only about one-fourth the amount sunk monthly by U-boats during the previous period. Only about 45 per cent of these sinkings took place in the Atlantic, as about 40 per cent occurred in the Indian Ocean and another 15 per cent in the Mediterranean. The world-wide number of U-boats sunk monthly reached a peak of about 21 a month during this period. The world-wide exchange rate reached a new low of only $\frac{4}{5}$ of a ship (4800 gross tons) sunk by the average U-boat before it itself was sunk.

U-boat activity in the Mediterranean was slightly lower than in the preceding period. Sicily was invaded in July 1943 and the Mediterranean was considered open for Allied shipping, although almost all of it was forced to travel in convoy. Only 36 merchant vessels were sunk by U-boats during this period at a price of 23 U-boats sunk.

Shipping losses to German and Japanese U-boats in the Indian Ocean were at a slightly higher level than previously as 71 ships were sunk during this 11 month period. However, this was the first period in which there was some evidence of countermeasures against the U-boats in the sinking of seven U-boats. This was one of the few areas where the exchange rate was still favorable for U-boat operations as 10 ships were sunk by U-boats for each U-boat sunk.

Japanese U-boats were strictly on the defensive in the Pacific and spent most of their time in supplying isolated outposts. Despite the fact that the bulk of the shipping in the Pacific sailed independently, only one merchant vessel was sunk by U-boats during this 11-month period, while Allied forces, mostly surface craft and submarines, sank 24 Japanese U-boats in the Pacific.[a]

The average number of U-boats at sea in the Atlantic during this period was only 61, about 40 per cent less than the average number at sea during the previous period. These U-boats sank only eight ships of 44,000 gross tons per month in widely scattered areas of the Atlantic. The average U-boat in the At-

[a] Four more Japanese U-boats were sunk in the Indian Ocean.

lantic reached a new low in offensive power as it was able to sink only 1/8 of a ship (700 gross tons) per month at sea.

Despite the meager results achieved by the average U-boat and the smaller number of U-boats at sea, the number of U-boats sunk in the Atlantic continued to increase as 16 were sunk monthly during this period. The average life of a U-boat at sea in the Atlantic during this period was, therefore, only about 4 months, half the average life of a U-boat at sea in the previous period. This meant that the average U-boat at sea in the Atlantic was able to sink only ½ of a ship (2800 gross tons) before it itself was sunk. The magnitude of the disaster which the U-boats suffered during this period may be roughly measured by the fact that the exchange rate (ships sunk per U-boat sunk) was about nine times as high in the previous period, the battle against the North Atlantic convoys, and about 38 times as high in the peak period, the first 9 months of 1942.

These figures reflected the growing strength and efficiency of Allied surface and air craft and the widening gap between Allied weapons and equipment and that of the U-boats. They also confirmed the German High Command's appreciation, at the beginning of this period, that the old-type U-boat could not compete any longer with Allied antisubmarine forces. The only consolation the enemy could have, at the end of this period, was that the U-boat losses would probably have been much larger than they actually were if the U-boats had actually continued their large-scale offensive against Allied shipping. This is indicated by a comparison of the 16 U-boats sunk monthly in the Atlantic with the 37 U-boats sunk in July 1943 and the 25 U-boats sunk in October 1943, the months in which the U-boats attempted offensive operations.

By operating their U-boats as they did, the Germans were able to maintain their large U-boat fleet for the invasion. About 250 new German U-boats were constructed during this period while only about 200 German U-boats were sunk so that the Germans had over 400 U-boats at the end of this period.

6.3.2 From the Allies' Point of View

The Allied and neutral nations lost about 184,000 gross tons of shipping monthly from all causes during this period, only about a third of the monthly shipping losses during the preceding period, while the construction of new merchant shipping ran at about 1,160,000 gross tons monthly, slightly higher than during the preceding period. Consequently, there was a net gain of about 976,000 gross tons a month in the amount of shipping available.

The shipping available to the Allies had increased by almost 11,000,000 gross tons during this period to a total of about 7500 ships of 47,500,000 gross tons. About 10,500,000 gross tons of this total consisted of tankers. October 1943 was the first month in which the total shipping available was larger than the 40,000,000 gross tons of shipping available at the start of the war, in September 1939. It took over four years to replace the heavy shipping losses caused mostly by U-boat action in the early years of the war.

By the end of this period, the shipping crisis had definitely passed and the Allies had sufficient shipping available to undertake the invasion. In fact, construction of new merchant shipping had started tapering off in 1944 after reaching a peak of 1,500,000 gross tons in December 1943. Part of this tapering off was due to the conversion of shipyards to the construction of the faster Victory ships which took about twice as long to build as the slower Liberty ships.

Of the 184,000 gross tons of shipping lost monthly from all causes, 147,000 gross tons were lost as a result of enemy action. U-boats accounted for 101,000 gross tons a month, about 69 per cent of the total lost as a result of enemy action. Monthly shipping losses due to enemy aircraft were higher than in the preceding period, amounting to 34,000 gross tons a month, about 23 per cent of the total due to enemy action. Shipping losses from enemy surface craft, mines, and other enemy action were even lower than in the preceding period, totaling only 22,000 gross tons a month, or 8 per cent of the total.

The major task of the Allies during this period had been accomplished. Sufficient supplies and men had been landed in England during this period to enable the Allies to undertake the invasion of Europe in June 1944. Although the U-boats were no longer the serious menace they had been in the past, the large U-boat fleet based on both flanks of the English Channel constituted a potential threat to the success of the invasion. The immediate problem facing the Allies, at the end of this period, was to prevent the U-boats from attacking the large concentration of shipping that would be carrying troops and military equipment across the Channel during the invasion. From a long-term point of view, it was necessary to

maintain the numerical and technical superiority of Allied antisubmarine forces over the U-boats. Allied antisubmarine forces faced the problem of preventing the U-boats from ever cutting the large and continuous flow of supplies that would be required by Allied fighting forces in Europe.

Chapter 7

SEVENTH PERIOD

SCHNORCHEL U-BOATS OPERATE IN BRITISH HOME WATERS

JUNE 1944–END OF WAR

7.1 U-BOAT OFFENSIVE

In many respects this last period of the U-boat war resembled the first period. The U-boat war was again subsidiary to, and largely influenced by, military operations in Europe. The U-boats were driven from their bases on the Bay of Biscay, which they had used for four years, and were forced to return to bases in Norway and the Baltic. The waters around the British Isles again became the main area of U-boat activity, as Schnorchel-equipped U-boats were able to operate in inshore waters with relative safety from aircraft detection. The U-boats were operating mostly submerged, not from choice as in the first period, but because they had been forced under by Allied aircraft. Surface craft again became the main destroyers of U-boats.

The U-boats found that operations in inshore waters were just as hazardous during this period as they had been at the beginning of the war. The chief difference was that during this period the average U-boat was able to sink only one-twentieth the amount of shipping that it sank in the first period. Allied escorts were more numerous, more experienced, and better equipped, while the U-boats' offensive power was greatly reduced by their loss of mobility. U-boat morale was also much lower during this period than it had been early in the war.

The lull in U-boat activity ended with the Allied landings in Normandy on June 6, 1944. The Allies had appreciated that the U-boats were a very serious potential threat to the success of the invasion. The size of the U-boat fleet at that time was still such that a mass attack in the Channel on D-day, from both flanks, might have saturated the defenses and inflicted grave losses on Allied convoys during the critical early days of the operation.

The Allied countermeasures involved blocking off the cross-Channel Area and guarding the convoy routes leading to it, with the object of making the approaches to both a difficult and exhausting operation for the U-boats. By June 6, ten escort groups, consisting of 54 ships, were ready to block the western approaches to the Channel. They were supported by three escort carriers, which were there chiefly to provide fighter support to escorts operating close to the enemy shores. The enemy air threat proved, however, to be so slight that these carriers were withdrawn by June 11. Coastal Command aircraft put on an intensive flying effort in the Channel and its western approaches and also in the Bay of Biscay Area. These dispositions of anti-U-boat forces were independent of, and in addition to, the escorts and aircraft provided for close escort duties with the convoys running to and from France.

The first reaction of the U-boats to the invasion was a considerable exodus of U-boats from the French ports on D-day, as soon as the enemy woke up to the fact that the operation had really started. The number of U-boats in the Biscay-Channel Area increased from one on June 5 to about 20 on June 8. The majority of these U-boats made no attempt to enter the Channel but, instead, set up defensive patrols off the Biscay ports to counter possible invasion attempts in that area.

A curious feature of these operations was that they began with a large number of sightings and attacks on U-boats by aircraft and then, after a period of several days, the number of contacts was sharply reduced. This reduction was due to the extensive use of Schnorchel by the U-boats, which had begun at that time. It seems that the U-boat captains had not taken very kindly to the Schnorchel with all the discomforts that it was capable of causing in inexperienced hands, and intended to use it only as a last resort, if the weight of air power against them became intolerable. After six U-boats were sunk by aircraft attacks in the Biscay Area between June 7 and 10, the U-boats began to appreciate the value of Schnorchel and quickly learned how to use it efficiently.

It is also possible that the enemy intended to operate his U-boats in the Channel, accepting all risks and proceeding on the surface in order to reach the vital invasion area and disrupt the Allied landing

operations. It was the initial blows dealt him by Coastal Command in the early days of the operation that forced him to adopt the more cautious, and less effective, tactics of remaining continuously submerged, which the advent of Schnorchel gave him the means of doing. The Schnorchel was a very poor radar target, even at short range, and was difficult to sight, even in daylight. To attack it at night required exceptionally good radar tracking and Leigh-light or flare technique.

In addition to their successes in the Bay of Biscay, Coastal Command aircraft contributed an outstanding performance in June against U-boats in Norwegian waters. Most of these U-boats were probably en route for the English Channel to join in operations there. These U-boats continued to operate mainly on the surface, and Coastal Command aircraft sank seven in Norwegian waters during June.

The first surface craft kill in the Biscay-Channel Area did not come until June 18. This was followed by four other surface craft kills, two with the help of aircraft, before the end of the month. There was only one aircraft kill in the Biscay-Channel Area between June 11 and the end of the month.

The U-boats obtained their first successes against merchant shipping in the invasion area more than three weeks after D-day, and sank five ships in the last few days of June. Two escort vessels were torpedoed by U-boats in the middle of June. When these results are measured against the 12 U-boats sunk in the same area in June by Allied forces, it is clear that the U-boats failed completely in their attempt to disrupt the Allied invasion.

The other enemy weapons (aircraft, surface craft, and mines) were equally ineffective against the thousands of Allied ships that moved across the Channel to Normandy. Only 18 ships of 75,000 gross tons were sunk in the Biscay-Channel Area in June 1944, as a result of all forms of enemy action. The Allies scuttled over 50 merchant vessels of about 300,000 gross tons in constructing the artificial ports that were used so successfully during the invasion.

The enemy turned to other offensive weapons in July, such as the human torpedo, explosive motor boats, and the V-1 bomb, but they did very little damage to Allied shipping. The experience in the Biscay-Channel Area during July and August was similar to that in June. The Allies continued to keep up their pressure on the U-boats, while the U-boats found the approaches to the shipping lanes so difficult that those who reached them fumbled the opportunities they found. U-boats operating in this area sank only two merchant vessels in July and six in August, while the Allies sank nine U-boats in July and 12 in August.

Surface craft played the predominant role in sinking U-boats in this area during these two months, killing 13 of them alone and destroying three others with the assistance of aircraft, out of the total of 21 sunk. An outstanding feature of the surface craft attacks in the invasion area was the difficulty experienced in the initial detection of U-boats which adopted anti-Asdic tactics of resting on the bottom when escort vessels were heard approaching. Numerous wrecks, together with the difficult water conditions and the high reverberation background in shallow waters, gave the U-boat almost complete immunity from Asdic detection. However, once the Asdic picked up the U-boat contact and identified it as such, the chance of obtaining a kill rose to a peak of about 50 per cent in the invasion operation.

The Second Escort Group continued its brilliant career during a ten-day patrol in the Biscay-Channel Area early in August. It achieved the first destruction of a U-boat by Squid and also took part in the sinking of two other U-boats. The Squid kill was remarkably quick. One pattern of six Squid charges was sufficient to bring the U-boat to the surface, and the crew rapidly abandoned the sinking U-boat.

The breakthrough of Allied land forces across the Cherbourg peninsula in the first week of August threatened the enemy's Biscay ports and forced their evacuation. The U-boats abandoned their efforts on the Biscay-Channel Area toward the end of August and headed for Norwegian ports. This marked the end of the first phase of the U-boat campaign against cross-Channel Allied shipping.

The enemy concentrated his main effort against the Allied invasion during the first three months of this period, and U-boat activity in other areas was slight. The average number of U-boats at sea in the Atlantic during June 1944 was about 48, and over half of these were concentrated in the Biscay-Channel Area and the Northern Transit Area–East. World-wide shipping losses to U-boats continued to be low as only 11 ships of 58,000 gross tons were sunk by U-boats in June. Besides the five ships sunk in the Biscay-Channel Area, there were three ships sunk in the rest of the Atlantic and three ships sunk in the Indian Ocean.

FIGURE 1.—Boarding party from USS *Guadalcanal* labors to keep the captured U-505 afloat after its crew had abandoned it to sink.

The total number of U-boats sunk during June was 28, about the same as the high level reached in May. Besides the 24 U-boats sunk in the waters around the British Isles, four others were disposed of in widely distant parts of the Atlantic by U. S. escort carrier groups. One of these four was U-505, which was captured by USS *Guadalcanal* [CVE] and her escorts on June 4, 1944.

This task group sailed from Norfolk in May 1944 with the avowed intention of capturing an enemy submarine. It was felt that there was a good opportunity to capture a U-boat that surfaced, by concentrating anti-personnel weapons on it, holding back on weapons that would sink it, and making an attempt to board it as soon as possible. After an unproductive hunt around the Cape Verde Islands, a well-conducted search plan was put in operation on May 31 for an estimated homebound U-boat. The USS *Chatelain* [DE], one of the escorts, made sonar contact at about 1000 on June 4. A Hedgehog attack, followed by a shallow depth-charge attack, brought the U-boat to the surface at 1023 and fire was opened. The U-boat crew scrambled on deck and dived overboard. At 1027, "Cease firing" was ordered.

The U-boat was then running in a tight circle at about seven knots, fully surfaced, and it was known that most of her crew had abandoned her. USS *Pillsbury* [DE], another escort, lowered a whaleboat with a boarding party and then attempted to rope the U-boat. Meanwhile, the boarding party got alongside and leaped from the whaleboat to the deck of the circling U-boat. There was only one dead man on deck and no one below, and the boarding parties immediately set to work closing valves and disconnecting demolition charges. The *Guadalcanal* took the U-boat in tow, but many difficulties were encountered as the towlines broke and the U-boat showed signs of settling. It was not until June 8 that the U-boat was at fully surfaced trim. This was the first time that a U-boat had been captured by the U. S. forces.

U-505 was finally brought to Bermuda and the

FIGURE 2. A torpedo plane approaches for a landing while USS *Guadalcanal* tows U-505 astern.

Allies were able to extract a great deal of extremely valuable technical information from the manuals and equipment aboard the U-boat. In addition to more reliable data on the acoustic torpedo, German search receivers, and other standard U-boat equipment, the Allies obtained important information about German war orders, communications, and codes. Much of this information proved to be of value in conducting later operations against the U-boats, as the Germans did not know that we had captured a U-boat and obtained this information.

World-wide shipping losses stayed low in July 1944 as only 12 ships of 63,000 gross tons were sunk by U-boats. In addition to the two ships sunk in the Biscay-Channel Area, five ships were sunk in the rest of the Atlantic and five in the Indian Ocean. The number of U-boats sunk throughout the world in July was 22, slightly less than in June. Escorts of USS *Card* [CVE] eliminated a potential threat to Allied shipping by sinking a 1600-ton minelaying U-boat early in July. This U-boat carried 66 mines, the moored acoustic type, which were intended to be laid in the approaches to Halifax.

August 1944 was the best month of this last period for the U-boats, as they sank 18 ships of 99,000 gross tons throughout the world. This peak score, however, is only about the same as the average monthly sinkage achieved by U-boats during the previous period, which was a rather low average, at that. Besides the six ships sunk in the Biscay-Channel Area, there were only two ships sunk in the remainder of the Atlantic. U-boats sank one ship in the Black Sea and nine ships in the Indian Ocean, mostly off East Africa in the Mozambique Channel. The landings in Southern France took place during August without the loss of any ships in the entire invasion area.

The downward trend in the number of U-boats sunk monthly continued during August as only 17 were sunk. Aircraft found it more difficult to detect and attack the Schnorchel U-boat. Apart from the 12 U-boats sunk in the Biscay-Channel Area, there were only three U-boats sunk in the Atlantic, all by escort carrier task groups. Aircraft from HMS *Vindex*, which was escorting the North Russian convoys, sank two U-boats, while aircraft from the USS *Bogue* sank U-1229 south of Newfoundland, after a 20-day search. This U-boat, traveling on Schnorchel, had remained submerged for about 11 days, surfacing only for a short daily interval of 10 to 15 minutes to determine her position.

The most significant development in August, with regard to future U-boat operations, was the advance of Allied armies in Western France which forced the U-boats to abandon their bases on the Bay of Biscay. These bases contained the redoubtable Todt concrete shelters which had withstood heavy Allied attacks for years. The basic strategy of German naval warfare in the Atlantic had depended upon the successful use and maintenance of the Biscay bases, from which U-boats could proceed directly to their operational areas with minimum fuel consumption and less throttling opposition from Allied air and surface patrols.

By the end of August it was evident that the U-boats had begun their final exodus from the Biscay ports and were heading for Norway, where they would be much more vulnerable to Allied air attack. The problems of repair and maintenance of a large U-boat fleet at the small and inadequately equipped Norwegian bases would also be much more difficult. The main effect, however, of the loss of the Biscay bases was the considerable increase in the length of voyages to operating areas. The 500-ton U-boats, which comprised the majority of the U-boat fleet, were thereafter restricted to operations around the British Isles, as it was extremely difficult to refuel at sea. Even the 740-ton U-boats confined most of their later operations to the nearby Atlantic, operating near Canada and Gibraltar.

During September 1944 the enemy seemed to be concerned primarily with shifting his U-boats from the Bay of Biscay to Norwegian bases. About 25 U-boats were engaged solely in running the gauntlet of Allied air and surface patrols between France and Norway. These U-boats traveled submerged for almost the entire trip, using Schnorchel, and most of them completed the journey safely. As a result of this mass transit of U-boats, the average number at sea in the Atlantic reached a peak for this last period during September when there were 57 U-boats at sea.

World-wide shipping losses were considerably reduced in September as only seven ships of 43,000 gross tons were sunk by U-boats. A noteworthy feature was the almost complete absence of U-boat activity in the Indian Ocean. One ship was sunk there early in the month, but the U-boat responsible for this sinking withdrew towards Penang where it was torpedoed by a British submarine. Although the other six ships sunk by U-boats during the month were all lost in the Atlantic, not a single ship was sunk in the formerly active Biscay-Channel Area. Two ships were sunk in the Barents Sea Area and one in the Canadian Coastal Zone. The other three ships were sunk early in September, from North Atlantic convoys, by U-boats operating on Schnorchel in inshore waters. These U-boats operated in the Northwestern Approaches to England, in an area of high shipping density through which the North Atlantic convoys passed on their way in and out of the North Channel. Fortunately, no further losses occurred in this area, as the Allies started routing the North Atlantic convoys around the south of Ireland at about this time.

The total number of U-boats sunk in September was 21. This included, however, six 300-ton U-boats that were scuttled in the Black Sea as a result of Russian advances in eastern Europe. In the Mediterranean, two of the three U-boats based at Salamis were destroyed. The general clearance of U-boats and enemy aircraft from the Mediterranean enabled the number of ships employed in convoy escort to be reduced and a large number of independent sailings was permitted. Only ten U-boats were sunk in the Atlantic. This steady decrease reflected the inactivity of the U-boats and the increased effectiveness of Schnorchel. Two of these U-boats were sunk as a result of the inshore activity in the Northwestern Approaches to England, five were sunk in the Northern Transit Area–East, and three in the remainder of the Atlantic.

By the end of September the last of the U-boats appeared to have departed from the Biscay-Channel Area. The average number of U-boats out at sea in the Atlantic declined to about 30 in October, with most of them still in transit. The results achieved by German U-boats reflect this situation, as October

1944 was the first month of the war during which they were not able to sink even a single ship in the Atlantic. As a matter of fact, the U-boats sank only one ship of 7000 gross tons during October. A perfect record for the month was spoiled on October 30, when a Japanese U-boat sank a U. S. cargo ship, traveling independently in the Pacific, midway between San Francisco and Pearl Harbor. Ironically, this was the first ship sunk in the Pacific by a U-boat since November 1943. The lull in U-boat activity was reflected on the east coast of the United States, as October was the first complete month of independent sailings for all ships engaged in coastal trade (except for dry cargo vessels of 8 to 10 knots).

Only nine U-boats were sunk during October, five of them in the Pacific and only four in the Atlantic. All four of the latter were sunk in the Northern Transit Area East, the area through which the U-boats traveled to and from their Norwegian bases. One of these four U-boats was sunk as the result of a bombing raid on Bergen. One of the five U-boats sunk in the Pacific was a German U-boat, sunk by the Dutch submarine HNMS *Zwaardvisch* in the Java Sea. This was by far the most easterly position in which a German U-boat had ever been destroyed.

Although the average number of U-boats at sea in the Atlantic during November was only 21, the lowest monthly average of this period, the enemy had completed his transfer of U-boats from the Biscay bases, and the U-boats at sea were more active. Seven ships of 30,000 gross tons were sunk by U-boats in November 1944: two ships in the Indian Ocean, a Swedish ship in the Baltic, and four ships in inshore waters in the Atlantic. Three of these ships were sunk on November 10 in the approaches to Rekjavik, Iceland. The other ship was sunk in the English Channel toward the end of the month after several months without any U-boat activity in this area.

The number of U-boats sunk during November was 10, but seven of these U-boat kills took place in the Pacific and only three in the Atlantic. This was the smallest monthly number of U-boats sunk in the Atlantic since January 1942. Two of these U-boats were sunk in the Northern Transit Area-East and one in the Biscay-Channel Area.

The main reasons for the meager results achieved by the Allies in sinking U-boats during these three months, September through November, was the extreme caution displayed by the U-boats as the average U-boat sank less than 1/10 of a ship per month at sea. Increased experience in the use of Schnorchel enabled the U-boats to avoid Allied air patrols by remaining submerged for prolonged periods and lying in wait for Allied convoys in focal areas inshore. Then, the U-boats developed their bottoming tactics in inshore waters, where wrecks and non-sub contacts were abundant and where the high reverberation background tended to drown out weak Asdic echoes. In addition, the necessity for the use of anti-Gnat noisemakers by Allied ships made Asdic detection more difficult.

The experience during these three months indicated to the enemy that U-boats could again operate in inshore waters, with Schnorchel, without suffering undue losses. This, in effect, made unnecessary the previous long voyages to distant areas which had been made in order to avoid the heavy Allied air coverage in the North Atlantic. The enemy, therefore, had by the use of Schnorchel overcome to some extent the great strategic disadvantage resulting from the loss of his Biscay bases. The use of Schnorchel enabled U-boats to proceed to and from their bases in Norway and the Baltic via the Faeroes-Shetland passage instead of the more circuitous passage south of Iceland. The U-boats could operate effectively in all areas of the North Atlantic, particularly in the waters around England, where the high density of important shipping provided an attractive target near the U-boat bases.

December 1944 witnessed the beginning of a steady increase in the number of U-boats at sea in the Atlantic. Coincident with the German land offensive on the Western Front (Battle of the Bulge), about five U-boats commenced operations in the central English Channel in an attempt to impede the flow of troops and supplies to the Allied armies in Europe. Seven ships and one escort were sunk by U-boats in the Biscay-Channel Area during December, with most of the damage being done toward the end of the month by two U-boats, both of whom escaped to tell of their success. During the same period an abortive offensive was launched by a flotilla of midget U-boats (Biber) against convoys in the Scheldt Approaches, off the Dutch coast. Only one ship was sunk while 15 midget U-boats were sunk or captured.

U-boat activity in other areas was slight during December as the world-wide shipping losses to U-boats totalled only nine ships of 59,000 gross tons. An independent ship was sunk in the Gulf of Maine on December 3 by the same U-boat that landed two

enemy agents on the coast of Maine on November 29. The other ship was sunk in the Pacific off the southeast coast of Australia by a German U-boat, the first sinking in these waters since May 1943.

Nine U-boats were sunk during December, one in the Indian Ocean and eight in the Atlantic. Six of the eight U-boats sunk in the Atlantic were lost in the waters around England, particularly in the Biscay-Channel Area and the Northern Transit Area-East. One of the three U-boats in the Biscay-Channel Area ran aground on Wolf Rock due to navigational difficulties.

U-boat activity continued to increase during January 1945 as 11 ships of 57,000 gross tons were sunk by U-boats. All 11 of these ships were sunk in the Atlantic by U-boats operating in inshore waters. In United Kingdom waters, there were no sinkings in the English Channel, although U-boats were still patrolling there, and the center of activity shifted to the Irish Sea, where six ships were sunk during the month by U-boats which had penetrated into the region, although it had long been considered safe from enemy attacks and had been used for training.

The other inshore areas of U-boat activity in January were off Halifax, where four ships were sunk and another damaged, and the western approaches to Gibraltar, where one ship and an escort vessel were sunk and another ship damaged. Three of the four ships sunk off Halifax were torpedoed on January 14, during daylight, out of a convoy nearing port. The escorts were not successful in locating the U-boat.

The number of U-boats sunk monthly reached a low for this period as only six U-boats were sunk during January, one in the Pacific and five in the Atlantic. All of these kills were made by surface craft during the latter half of the month. Not a single U-boat was sunk by aircraft during January 1945. The first of these sinkings occurred on January 16, when a U. S. destroyer escort task group sank a weather-reporting U-boat in the Northwest Atlantic Area. Using information based on the U-boat plot, the group departed from the Azores for the general area of the last fix. An HF/DF fix, at a range of 10 miles, further localized the probable area of the U-boat and the hunt got underway. Some 2½ hours later, sonar contact was gained, and one Hedgehog attack and five Mk 8 depth-charge attacks resulted in the sinking of the U-boat.

The other four U-boats sunk in the Atlantic during January were all sunk in United Kingdom coastal waters by British surface craft. Three of these kills resulted from Asdic contacts made shortly after ships were torpedoed. They were particularly encouraging in that they represented some evidence that ships were finally learning how to attack U-boats operating in inshore waters, after months of disappointing patrols in generally difficult conditions.

In addition to these successes, indirect but effective anti-U-boat operations were carried out by the Russian armies during January. By overrunning East Prussia, they threatened the important working-up bases in the eastern Baltic, and by entering Silesia they paralyzed part of the elaborate organization for the construction of the new type U-boats. It is estimated that the yards at Danzig alone produced almost a third of the new Type XXI prefabricated U-boats. Not only were the Norwegian and western Baltic ports severely taxed by assuming the additional burden of handling surface vessels and U-boats previously based in the eastern ports, but the concentration of all U-boat facilities in the western Baltic made them much more vulnerable to Allied air attacks.

The U-boats were more aggressive in February 1945 and sank 15 ships of 65,000 gross tons. One ship was sunk in the Indian Ocean, off the west coast of Australia, and the other 14 ships were sunk in the Atlantic, the peak monthly score for this period. With the land warfare in Europe approaching Germany, the enemy's objective seemed to be to sink the maximum shipping in the short time remaining. Consequently, the major U-boat effort was concentrated in British coastal waters, where nine ships were sunk during the month, mainly in the southwest approaches to the English Channel and in the North Sea off the east coast of England. The five ships sunk in the remainder of the Atlantic included two in the Barents Sea Area, one near Iceland, one near Gibraltar, and one in the Southeast Atlantic by a U-boat homeward bound from the Indian Ocean.

The number of U-boats sunk monthly increased sharply as 19 U-boats were sunk in February, indicating that the kills near the end of January initiated a new period of good hunting. Twelve of the 14 U-boat kills in the Atlantic took place in the waters around England, but there was a shift of activity to the northward. The Tenth Escort Group carried out a particularly successful patrol in the area between the Shetlands and the Faeroes against U-boats on

passage to their operational areas, sinking three of them. These three attacks all resulted from initial Asdic contacts on submerged U-boats. Ten of the 14 kills in the Atlantic were made by surface craft as Asdic was becoming much more effective against U-boats in shallow inshore waters due to the increased experience of Allied ships under these conditions. The other two U-boat kills in the Atlantic occurred in the Barents Sea Area and off Gibraltar.

Five Japanese U-boats were sunk during February in the Pacific, where the U. S. submarine USS *Batfish* turned in a record *performance* by sinking three U-boats in four days. These were torpedoed north of Luzon between February 9 and 12. In each case, the *Batfish* detected Japanese radar signals on her search receiver [APR] and then homed on the U-boat.

The number of U-boats at sea in the Atlantic increased sharply in March 1945, averaging over 50 for the month. Most of these were concentrated in the waters around England, but there were some signs of a shift of U-boat activity to deeper waters in the Atlantic, possibly indicating that the enemy had appreciated that some escorts had been removed from ocean convoys to operate in inshore waters. There was also some evidence that Type XXIII U-boats operated in the North Sea, off the east coast of England.

Despite the increase in the number of U-boats at sea, the world wide shipping losses to U-boats stayed at the same level in March 1945 as only 13 ships of 65,000 gross tons were sunk by U-boats, all in the Atlantic. Nine of these ships were sunk in the waters around England, seven of them in the Biscay Channel Area. Two ships were sunk in the Barents Sea Area and another two were sunk in the Brazilian and Caribbean Areas by a U-boat homeward bound from the Indian Ocean. Midgets probably sank another three ships in the North Sea Area.

The number of U-boats sunk during March continued high as 19 were destroyed, 2 in the Pacific and 17 in the Atlantic. Four U-boats were destroyed by our raids in German ports and one was sunk in the Canadian Coastal Zone by a U. S. destroyer escort killer group. The other 12 U-boats were sunk in the waters around Great Britain; one by aircraft, two by mines, and nine by surface craft. The Twenty-First Escort Group turned in a notable performance by sinking three U-boats in four days, north of Scotland.

In April 1945, shipping casualties were of the same order of magnitude as in March, as 13 ships of 73,000 gross tons were sunk by U-boats. All of these ships were sunk in the Atlantic: two off Cape Hatteras in Eastern Sea Frontier, one in Kola Inlet in the Barents Sea Area, and the other ten in coastal waters around England, mainly in the Channel Area.

The tempo of U-boat operations in April gave no indication that the end of the war was at hand. With remarkable determination the enemy maintained his U-boat offensive in inshore waters to the very end of the war. No relaxation of effort or hesitation to incur risk was apparent until the German surrender on May 8, 1945. A U. S. cargo vessel was sunk off Rhode Island on May 5, but a U. S. destroyer escort task group gained sonar contact later that night and destroyed the U-boat. On May 7, a U-boat sank two merchant ships from a coastal convoy near the Firth of Forth. These were the last merchant ships sunk by U-boats in World War II, as Japanese U-boats did not sink a single merchant ship between V-E Day, May 8 and V-J Day, August 14, 1945, while six Japanese U-boats were sunk in that interval.

The 36 U-boats sunk during April 1945 made the highest monthly score of the last period. Five of these U-boats were sunk in the Pacific and the other 31 were sunk in the Atlantic, with surface craft accounting for 19 kills, the highest monthly score of the war for them. Twenty two of these U-boats were sunk in the waters around England, three in the Barents Sea Area, two along the east coast of the United States, and four in Northwest Atlantic Area. These four U-boats were part of a group of six (Group Seawolf) engaged in a joint westward sweep of North Atlantic convoy lanes while en route to operations off the U. S. coast. Escorts of U. S. escort carrier task groups that conducted a barrier patrol which intercepted this group of U-boats were responsible for these four kills. On the last day of April, a U. S. Navy MAD-equipped plane sank a U-boat in the Biscay-Channel Area with retro bombs.

During the first week of May, aircraft operated with great effectiveness in Danish waters against U-boats attempting to escape to Norway, sinking about ten of them with rockets and gunfire. In addition to the kills enumerated above, it is estimated that the heavy bombing raids on German ports in the Baltic probably accounted for the destruction of over 25 U-boats in port during the last month of the war.

On May 4 a short signal was transmitted on all U-boat frequencies. By this signal, Doenitz had

ordered his U-boats to cease hostilities. In an Order of the Day issued at the same time, he explained that a crushing superiority had compressed the U-boats into a very narrow area and that the continuation of the struggle was impossible from the bases which remained. By May 31, 49 U-boats had surrendered at sea leaving a small number unaccounted for. The last of these to turn up was U 977 which surrendered at Buenos Aires on August 17, 1945, after the surrender of Japan. In addition to the U-boats which surrendered at sea, huge numbers were captured in ports or scuttled.

The end of the war thus saw the U-boat fleet held in check but still carrying out operations on a major scale. It had never been driven off the seas and might well have increased substantially in numbers and power, had the war been extended for any appreciable period. New type U-boats were just coming into service at the end of the war. About six Type XXIII U-boats had operated with fair success off the east coast of the United Kingdom and at least that number of Type XXI U-boats had reached ports in Norway with the intention of sailing in the immediate future for offensive operations. One is believed to have actually started on patrol, but it was forced to turn back due to some failure in equipment. The U-boat was by no means eliminated as a weapon of war when Germany surrendered, and the new types which Germany was introducing would have raised serious problems for the Allies had they ever reached large scale use.

7.2 COUNTERMEASURES TO THE U-BOAT

7.2.1 Convoys

Shipping in convoy during this last period was safer than in any previous one. Although the number of convoyed ships at sea was at its peak, only six ships were sunk monthly by U-boats. Of the 1100 ships that sailed monthly in the North Atlantic convoys, only about one was sunk monthly by U-boats, usually in the vicinity of England. The loss rate was therefore less than 1/10 of 1 per cent.

The proportion of shipping sunk by U-boats, which was in convoy when sunk in contrast to independent sailings, increased to about 55 per cent during this period. This increase was due to the fact that U-boats, operating on Schnorchel in inshore waters, found it desirable to operate in areas of high shipping density, that is, along the convoy lanes. The experience during this period differed from the past in that most of the shipping losses occurred at the terminals of the convoy routes, instead of in the middle.

The principle of defense in depth contributed greatly to the safety of convoyed shipping, particularly in the case of the North Russian convoys. During this last period, there were often sufficient ships available so that, in addition to the close escort, pickets could be stationed in an outer screen. Pickets could intercept surfaced U-boats, investigate surface ships, divert neutral ships, and give the Escort Commander timely warning of impending dangers. Air patrols operated in the zone beyond the pickets.

The largest convoy of the war, HXS 300, consisting of 167 ships and seven mid-ocean escorts, sailed in July 1944. With 19 columns, this convoy had a front of some nine miles. The ships in the convoy carried over a million tons of cargo to England. The convoy arrived safely and the fact that it was not attacked may well have been due to the vigorous search by aircraft of the two MAC ships for the only U-boat reported in the vicinity.

Early in September 1944, following the transfer of the U-boats from the Biscay base to Norwegian ports, the Allies rerouted the North Atlantic convoys around the south of Ireland, through St. George's Channel. Although not shortening the voyage between New York and Liverpool to any appreciable extent, the southerly route did facilitate the joining and splitting of sections from and to the south coast of England and the Continent. It also got further away from both the U-boats based in Norwegian and German ports and the rough weather of the higher latitudes. Convoy CU 37 was the first to sail to an Atlantic port on the Continent, as one section arrived in Cherbourg on September 7. Antwerp was opened to Allied convoys on November 28.

The increased safety of convoys in the Atlantic enabled the Allies to make another change that would quicken the flow of shipping. Towards the end of September 1944 the sailing interval for the HX and ON convoys was reduced to 5 days and the slow SC and ONS convoys were started again. This meant that the convoys would not be as large as they had been in the previous months, but there would be more of them. The time spent in port by ships waiting for convoys was cut materially by this change.

Similar steps were taken in the East Atlantic in November 1944. A single escort sailed with convoys between Gibraltar and the United Kingdom, although additional protection was given at both ends. This more or less restored the arrangement which had been in force from the outbreak of the war until the middle of 1941. Shipping between Gibraltar and Freetown was permitted to sail independently if there were no U-boats along the route. In the Mediterranean convoying was abandoned except for troopships and local convoys near Italy and Greece.

In the last month of the war, April 1945, the average number of ships at sea in the Atlantic reached a maximum of 1400, about double the number in the early months of 1943. About two-thirds of these ships were in convoy. Shipping in the Pacific also reached a new high in April, as there were about 900 ships at sea, with about one-third of them in convoy.

7.2.2 Aircraft

Most of the U-boat activity during this period was concentrated in the waters around England and consequently aircraft under Coastal Command operational control played the major part in the offensive against the U-boats. At the end of the war, Coastal Command had more than 1100 planes under its control, more than six times the number available at the start of the war. The invasion battle started in May 1944, when U-boats left from Norwegian ports to reinforce the Biscay ports for the attack on the huge amount of Allied shipping which would have to be used for the build-up of the Allied beachhead. Very few U-boats got through, as aircraft sank 17 U-boats and damaged 11 others in Norwegian waters between mid-May and the end of July. Thus a depleted U-boat fleet was left to execute the plan to attack the invasion traffic.

As soon as the invasion had started, the U-boats headed for sea, staying on the surface and fighting back against aircraft with their automatic 37 mm gun. Coastal Command was ready, and within five days the enemy lost six U-boats while five were seriously damaged. The hectic few days after D-day produced one of the outstanding achievements of the war, when a Liberator sank two U-boats at night within half an hour. After the first week of the invasion, the enemy abandoned his ideas of staying on the surface and the all-Schnorchel era had begun. But the beachhead was already secure and the U-boat fleet badly mauled. Between mid-May and the end of July Coastal Command aircraft sank 23 U-boats, shared two kills with surface craft, and damaged 25 U-boats. The price paid for the success was 31 aircraft lost as a result of enemy action and 17 lost as a result of operational hazards.

Once the invasion beaches were secure, it became Coastal's job to protect shipping until victory was finally won. It was difficult to detect Schnorchel at all and even after it was detected, the probability of attacking it successfully was lower than that for an attack on a surfaced U-boat. All available aircraft were employed to hunt the Schnorchel and, although the number of kills was somewhat disappointing, only a few ships were sunk in inshore waters. Thus the many hours of flying often without the consolation of a sighting were not wasted.

With the reduced opportunities to kill U-boats, Coastal Command began to look further afield. During 1945, there were a number of anti-U-boat sorties in the Skagerrak, Kattegat, and the western Baltic. Liberators at night and rocket-fitted Mosquitos and Beaufighters during the day carried the war right into the U-boats' home waters. Numerous attacks were made, some of them on the new type U-boats which were proceeding to Norwegian ports prior to setting out on operations. The outstanding effort was a strike in the Kattegat by Mosquitos, which resulted in the sinking of three U-boats. In the final days of the war, the last real action was seen when U-boats began to evacuate north German ports and run for Norway. Many attacks were made and about ten U-boats are believed to have been sunk by aircraft in the first week of May 1945.

During the entire period aircraft operating under Coastal Command made about 38 sightings and 24 attacks monthly, about the same as in the previous period although the concentration of U-boats in British waters was much higher in the last period. The use of Schnorchel resulted in a reduction in the lethality of aircraft attacks, as only 18 per cent of them resulted in the sinking of a U-boat (about 25 per cent in previous period) and about 35 per cent of the attacks resulted in at least some damage to the U-boat. About half of the aircraft kills made during this 11-month period occurred in the first and last months (June 1944 and April 1945), when a high proportion of the U-boats were found on the surface.

Operational results during the last period indicated that Schnorchel was a most effective counter-

measure to Allied air power. Most of the U-boats were equipped with Schnorchel, fitted with a drum-shaped aerial (Runddipol) which was pressure-tight, but gave warning only of meter radar. The primary effect of Schnorchel was to cut visual and radar ranges from Allied aircraft by a factor of about 2 or 3. Toward the end of this period the Germans developed an effective anti-radar rubber-like covering for the Schnorchel, which was supposed to cut Allied microwave radar ranges on Schnorchel by another factor of 3. The ranges at which many radar contacts would first be made were such as to place them within the sea return zone of Allied radar sets, where they were missed entirely. It has been estimated that the number of potential Schnorchel contacts missed at short ranges is larger than the total number of Schnorchel contacts made at all ranges.

These advantages of Schnorchel enabled U-boats to operate over long periods of time in restricted waters, with reasonable safety from aircraft, by remaining bottomed most of the time and coming to Schnorchel depth only to recharge batteries. The effectiveness of aircraft hunts was also reduced as the Schnorchel increased the submerged speed of U-boats for prolonged periods from about 2 or 3 knots to about 6 knots.

Schnorchel, however, also had its disadvantages. The offensive power of U-boats was greatly reduced as they were forced to give up the great mobility of surfaced operations for the relatively slow speeds of Schnorchel operation. The efficiency of the periscope watch was impaired when the U-boat was at Schnorchel depth, and the noise of the engines rendered the hydrophones practically useless. In addition, prolonged use of Schnorchel undoubtedly increased personnel fatigue, as a result of varying air pressure, occasional fumes, and the more careful attention required to maintain depth control.

Despite these disadvantages, the U-boats preferred the feeling of security which the Schnorchel gave them to the alternative of operating on the surface, and depending on their new directional microwave search radars for warning of aircraft. With the increased use of Schnorchel, the number of U-boat contacts per 1000 flying hours steadily decreased and the ratio of Schnorchel contacts to all contacts steadily increased, passing the 50 per cent mark in December 1944. Visual search became relatively more productive than radar search as occasional sightings at relatively long ranges were made on the exhaust smoke or wake that sometimes accompanied the Schnorchel.

The Allies were not able to produce any really effective countermeasures to the Schnorchel by the end of the war. Increased stress was placed on the use of binoculars in visual search and the most favorable altitudes for the detection of Schnorchel were determined. Tactical doctrines were modified to take account of the decreased sweep widths of both radar and visual search. Modifications, such as the fast time constant [FTC] circuit, were made to Allied radar sets to improve the efficiency of contact. The FTC circuit acted as a discriminator against sea return, thereby making it easier to distinguish the Schnorchel blip. New high-power narrow-beam short-pulse radar sets were designed to provide better resolution in search for small targets. Tests indicated that the new radar sets (AN/APS-3 and AN/APS-15), which operated in the X band (3-cm) and had sharp beams, were better at detecting Schnorchel than the earlier longer-wave-band radar sets.

Aircraft used sono-buoys more frequently towards the end of the war in order to take advantage of the high noise output of Schnorchelling U-boats. Sono-buoys had been used successfully in a number of attacks by aircraft and escorts of U. S. escort carrier task groups and analyses indicated that in over 50 per cent of the cases in which sono-buoys were dropped following visual contacts on U-boats a sono-buoy contact was obtained.

7.2.4 Scientific and Technical

The Allies continued to perfect their equipment and tactics during this last period. More useful and flexible retiring search plans were developed for surface craft. Operation Observant and similar search plans, based on the most probable location of the U-boat, provided ships with the means of regaining contact with a U-boat once the general location was known. An analysis of surface-craft hunts indicated that when the correct plan was used, contact was regained in 44 per cent of the cases, while the incorrect plan led to success in only 28 per cent of the cases.

The U. S. Navy continued to improve its sonar equipment as experimental work was done with maintenance of deep contact feature [MDC] and depth-determining gear. By the end of the war a new fast sinking influence depth charge had been developed, the Mark 14, which was considered to have

higher probability of doing lethal damage to a submerged U-boat than other depth charges. This charge was designed to fire at the nearest point of approach to a U-boat by the change of frequency between the reflected signal and the supersonic signal emitted by the depth charge.

An analysis was made of the operational results obtained during 1943 and 1944 by British ships using depth charges, Hedgehog, and Squid. It indicated that a single depth charge pattern had about a 5 per cent chance of sinking a U-boat and a Hedgehog pattern at least a 15 per cent chance, while the Squid attacks averaged about a 20 per cent chance of success. The double Squid pattern showed promise of being the most lethal weapon against U-boats, but this was based on a small number of attacks.

The greatest technical effort of the Allies, however, was spent on the effort to develop satisfactory means for the detection of Schnorchel. As previously mentioned, two main lines were followed: (1) the improvement of radar performance by choosing a design effective against small targets, and (2) the improvement of sonar detection, in particular sonobuoys for detection from aircraft. The chief modification involved was increase in the operating life of the buoys to reduce the number that had to be employed. In addition, directional sono buoys were developed, which gave a more accurate submarine position, but these did not see operational use.

The U-boat command again was prolific in developing new technical equipment for the U-boats in an effort to stave off the impending defeat. During 1944 the Germans introduced a new type of gear [LUT] on their torpedoes which enabled the line of advance of the torpedo, when zigzagging, to be preset at any angle from its straight run. This gear also enabled the mean speed of advance to be preset at will. At the end of the war the Germans were developing a new type of homing torpedo (Geier) which emitted supersonic signals and homed on the reflected echoes from the target.

During this period, the Germans modified their 740- and 1200-ton U-boats to enable them to dive as quickly as the 500-ton U-boats. The most distinctive feature of these modified U-boats was the narrow cut-away deck forward.

Toward the end of the war, there were some indications that the Germans had developed an ultra high-speed method of communication (Kurier) using an attachment to the normal U-boat transmitter. It appears that the message was recorded on a magnetic tape which was then run through at high speed. This method of communication would counter Allied use of HF/DF.

Early in 1944 the U-boat command had come to a clearer appreciation of the true situation with regard to the Allied use of radar. They realized that they needed an improved search receiver against S-band (10-cm) radar which would not only give ample warning but would provide a margin of sensitivity against inevitable losses of efficiency under operational conditions. The enemy had also learned of X-band (3-cm) radar from a crashed H_2X blind bombing plane at the beginning of 1944 and the development of X-band search receivers was started by the Germans before Allied use of X-band radar in U-boat search had produced many results.

The German solution to these problems appeared in the late spring of 1944 in the form of the "Tunis" search receiver. Tunis consisted of two antennas, the "Mucke" horn for X-band radar and the "Cuba Ia" (Fliege) dipole and parabolic reflector for S-band radar, fitted with an untuned crystal detector and connected to a Naxos 2 amplifier. Bearings were taken by rotating the DF loop on which the antennas were mounted. The X-band Mucke horn had a beam width of about 15° so that bearings on 3-cm radars were quite accurate. The S-band Fliege antenna detected 10-cm radar transmissions through a sector of about 90°.

The chief feature of this equipment was the directional antennas, which gave increased sensitivity and range. In order to obtain the necessary sensitivity with these aerials, the Germans had to sacrifice the desirable property of all-around looking and the aerials had to be continuously rotated by the bridge watch. The units still had to be dismounted and taken below on submergence, and so could not be used on Schnorchel.

Allied tests on captured equipment indicated that Tunis was simple to operate and dependable under normal operational conditions. These tests indicated that expected operational ranges on Allied radar sets would vary from about 20 miles for planes at 500 feet altitude to about 40 miles for planes flying at 2000 feet. These expected operational ranges of Tunis were greater than the corresponding average radar ranges, both for S-band and X-band, on surfaced U-boats. It was concluded that the Tunis search receiver was apparently a simple, efficient, and suc-

cessful countermeasure to both S-band and X band radar.

The Tunis search receiver was used very infrequently by U-boats during this period and it is quite possible that the Germans were not aware of how successful it could be against Allied radar. Tunis was developed shortly after Schnorchel had been fitted to the U-boats and never did receive a fair trial in actual operations. The U-boats apparently did not have much faith in their technical experts, who had fumbled so badly in 1943, and preferred the security offered by Schnorchel, despite its limitation for the offensive, to the risk of operating on the surface and depending on Tunis for early warning of Allied aircraft. Then again Tunis offered no protection against possible new Allied radar sets on different frequencies or against Allied aircraft not using radar at all, while Schnorchel did. It seems quite likely that the U-boats would have sunk considerably more shipping if they had operated on the surface with Tunis, but the desire for safety was predominant and Schnorchel offered the better prospects for that.

All the centimeter aerials produced by the Germans had the disadvantage that they could not withstand submergence. The production of a suitable pressure-tight aerial, urgently needed for use on Schnorchel, presented great technical difficulties which were not completely solved at the end of the war. The only search receiver aerial that was fitted on Schnorchel was the old standard Runddipol type, which could detect only meter radar. There were some signs that the Germans were developing a pressure-tight aerial at the end of the war, suitable for both S-band and X-band radar detection and incorporating an infrared receiver as well.

During this period the Germans introduced a variety of midget U-boats (e.g.: *Seehund*, *Molch*, *Biber*, *Hecht*, and *Marder*), piloted by one or two men from a pressure-tight control position and capable of complete submergence. The successful attack by British midget submarines on the *Tirpitz* on September 22, 1943, stimulated German interest in these craft. The flotillas operating these midget U-boats were not branches of the U-boat arm of the German Navy but form part of an organization known as the Small Battle Units Command (KDK).

The *Seehund* (Type XXVII) was probably the most formidable of the midget U-boats. It was prefabricated, about 39 feet long, and displaced 16 tons. It carried two torpedoes and a two-man crew. The surface speed was about 6 knots and submerged speed about 3 knots. The surface range was about 275 miles, the endurance of the crew about three days, and the diving depth about 100 feet. It was fitted with a periscope.

Midget U-boats were used primarily in the invasion area and were generally ineffective, inflicting very little damage on Allied shipping while suffering heavy losses. This may have been due partly to the fact that they were rushed into battle before they were perfected and before their crews were properly trained. Their small size made it more difficult to detect them but they were extremely vulnerable to depth-charge attack. They were relatively slow and unhandy, with a limited operational range, and only suitable for attacking merchant ships proceeding slowly in calm waters. It is estimated that about 80 midget U-boats were sunk or captured between December 23, 1944, when they started operations in the Channel Area, and the end of April 1945.

The heavy losses sustained by U-boats in the Battle of the Atlantic forced the enemy to undertake the gigantic task of building a complete new frontline U-boat fleet. Though faced with imminent invasion and with a great shortage of manpower, Germany employed a very large number of their skilled workmen in the construction of prefabricated U-boats. This is a measure of the importance that the enemy attached to U-boat warfare and of the hopes which he entertained for success in a new campaign.

The Type XXI U-boat was designed for high submerged speeds, primarily to get into a favorable attack position. Originally intended for turbine drive, the high speed hull design for the Type XXI was completed before the Walter propulsion unit was ready and it was actually equipped with extra large batteries to give the high maximum submerged speed of 15 to 18 knots. Its submerged endurance at a speed of 10 knots was about 11 hours. The type XXI U-boat was about 250 feet long and its standard displacement about 1600 tons. The large torpedo room with 6 bow tubes was an answer to the demands for increased armament. The U-boat carried a crew of 57 men and 20 torpedoes. Stern torpedo tubes were sacrificed to obtain greater speed. Silent-running speeds of about 5 knots were obtained on electric motors when submerged. An improved extensible type of Schnorchel was fitted. The Type XXI U-boat used diesel propulsion on the surface and had a maximum speed of 15 knots. It was a true ocean-

going U-boat and its surface endurance was estimated to be greater than that of a 740-ton U-boat.

The Type XXIII U-boat was developed on requirements from the Mediterranean U-boat command for inshore waters and short cruises. These characteristics were also useful for operations in the invasion area. The Type XXIII U-boat was about 111 feet long and its standard displacement was about 230 tons. It had two bow tubes and carried only two torpedoes. The total crew consisted of only 14 men. Its maximum surface speed was 10 knots and its maximum submerged speed 12 knots. The submerged endurance at 10 knots was about 1½ hours.

Both Type XXI and Type XXIII U-boats were built by a system of prefabrication which fell into four stages. Basic parts were manufactured at a number of widely dispersed factories situated along Germany's inland waterways. Sections of the hull were assembled at a number of shipyards and sent from them to certain key yards for welding into complete U-boats, which were then fitted out under covered shelters. The final assembly yards for the Type XXI U-boats were Hamburg, Bremen, and Danzig.

Speer's dispersal of his organization did much to defeat Allied bombing, but the indirect results of Allied raids were serious. The German transport system was disrupted by Allied bombing of communications and this did much to set back the time schedule for the construction of these new U-boats. The first prefabricated U-boat was completed in June 1944 and by the time the war ended, the enemy had completed about 120 Type XXI U-boats and about 60 Type XXIII U-boats. Both the new types, however, were put into production prematurely and defects discovered during trials and teething troubles had prevented them from becoming operational. The loss of the eastern Baltic ports and the heavy bombing of the western Baltic ports, together with mining of that area, further delayed the long awaited offensive by the new-type U-boats. About six patrols were made by Type XXIII U-boats in the North Sea before the end of the war. The immense effort put into developing Type XXI was a complete waste as it did not operate at all before the German surrender.

The Allies were forced, however, to develop countermeasures to the high speed U-boats. HMS *Seraph*, a British submarine, was converted so that she could make 12 knots for a limited time and trials were conducted to develop new tactics for use against the high speed U-boats.

Three Type XVII-B U-boats with turbine drive were completed before the end of the war. These were built for experimental purposes to obtain information on tactics and improvements for the Type XXVI U-boat, which was to be the perfect U-boat, incorporating all the advantages of earlier experience and the extremely high speeds available with the Walter propulsion units. The high speed obtained from turbines using hydrogen peroxide fuel was of limited duration and was only to be used in attacks or other emergencies. A diesel for cruising at Schnorchel depth and a small battery and electric motor for quiet running were to be used for all other purposes. There was no expectation of ever operating these U-boats on the surface.

The Type XXVI U-boat was intended to be about 184 feet long and to carry a crew of 37 men. The maximum submerged speed on turbines was to be 24 knots with an endurance of about 6 hours at that speed. Ten torpedoes were to be carried in four bow and six side torpedo tubes. Sound gear was to be used to direct torpedo fire from a submerged position and all ten torpedoes could be fired in one salvo.

It should be stressed at this point that no Type XXVI U-boats were ever built and that no Type XXI U-boats ever operated at sea before V-E Day. The conclusions developed in this history of World War II do not necessarily apply to these high submerged speed U-boats.

7.2.4 Sinkings of U-boats

The average number of U-boats sunk monthly during this period was 18, slightly less than during the previous peak period. This decrease was due primarily to the considerable drop in the average number of U-boats at sea. The total number of U-boats sunk during this 11-month period (June 1944 through April 1945) was 196, consisting of 161 German U-boats and 35 Japanese U-boats.

Over 80 per cent of the 148 U-boats sunk in the Atlantic were destroyed in the waters surrounding England, as 59 were sunk in the Biscay-Channel Area, 35 in the North Transit Area-East, 11 in the North Sea, and 13 in the Northeast Atlantic Area. The other 27 Atlantic U-boat kills were divided as follows: 7 in the Northwest Atlantic Area, 6 in the Barents Sea Area, and 14 in widely scattered parts of the remainder of the Atlantic, 9 of them in the west Atlantic and five in the east Atlantic.

Surface craft displaced aircraft as the leading killer of U-boats during this period, as most of the German U-boats operated on Schnorchel. Allied ships sank 92 U-boats alone (47 per cent of total) and another 15 (8 per cent of total) with the help of aircraft. Aircraft sank 57 U-boats (29 per cent of total). As most of the U-boats operated in inshore waters, carrier based aircraft played a smaller part during this last period accounting for only 11 of the 72 U-boat kills in which aircraft participated. Allied submarines sank 17 U-boats (9 per cent of total), most of them in the Pacific. The other 15 U-boats (7 per cent of total) were lost as a result of mines, marine casualties, and scuttling.

The quality of surface craft attacks reached its highest level during this last period as over 30 per cent of the attacks were lethal. This percentage reached a high of about 50 per cent during the invasion period, when U-boats first started operating on Schnorchel. It dropped to about 20 per cent as U-boats perfected their inshore tactics during the last quarter of 1944 and then increased again to about 30 per cent during the first few months of 1945, as British escort groups learned how to deal with the bottomed U-boat.

7.3 SURVEY OF RESULTS

7.3.1 From the U-boats' Point of View

Some idea of the attitude of U-boat crews and officers during this last period may be obtained from statements made by prisoners of war. Toward the end of 1943, many doubts and questions had arisen concerning the outcome of the war and the supposed superiority of German weapons. These doubts became stronger when, despite the many promises of new weapons made by the U-boat Command, practically none were supplied and the U-boats' situation steadily deteriorated. The former enthusiasm and confidence of the men in the power of their arms and in the competence of their leaders turned into a kind of lassitude, and resulted in a mechanical execution of commands. The phrase "orders are orders" characterized the typical state of mind. The majority of U-boat officer survivors expressed in no uncertain terms the opinion that the U-boat was no longer practicable as an offensive weapon in view of the effectiveness of Allied antisubmarine measures at that time. Despite their state of mind, the U-boats fought to the very end of the war with discipline unimpaired, and there were no signs of any collapse of the German Navy, such as occurred in 1918.

About 13 U-boats were sunk monthly in the Atlantic, slightly less than the previous figure of 16. The average number of U-boats at sea, however, had declined to 39 from the average of 61 in the previous period. This meant that the average life of a U-boat at sea in the Atlantic was only three months, even lower than the average life of four months in the previous period. Despite the use of Schnorchel and maximum submergence tactics, the U-boats found operation in inshore waters just as hazardous as they had been at the beginning of the war when the U-boats had to give up close-in submerged operations.

The exchange rate in the Atlantic was about the same as in the previous period as only 6/10 of a ship (3300 gross tons) was sunk by the average U-boat before it itself was sunk. U-boats operating in inshore waters where there was a heavy concentration of shipping were able to sink a little more shipping per month at sea during this period but this was balanced by the higher loss rate suffered by them.

The tactics evolved by the Schnorchel U-boat toward the end of the war involved practically no surfaced operations. In transit, navigation was by dead reckoning, radio-navigational fixes off the chain of "Electrasonne" transmitters and beacons, and also by echo sounder and periscope bearings of lights or points of land. Schnorchelling was mostly at night, for only about four hours in each 24. When Schnorchelling, a U-boat kept all-around periscope watch day and night, and constant meter-band GSR watch. Diesels were stopped once every 15 to 30 minutes to make an all-round hydrophone sweep. Once the U-boat was in the patrol area, it was a recognized tactic to lie on the bottom of a convoy route and to come up only when hydrophone contact was established. For aiming the torpedoes, the periscope was still virtually the only instrument available. Salvos of curly torpedoes were fired among the merchant ships, or else a single acoustic torpedo at either the convoy or an escort. The usual methods of evading Allied counterattacks were either lying on the bottom, or else proceeding at silent speeds of about 3 knots or less on electric motors.

The Schnorchel enabled U-boats to operate in the above manner in inshore areas. These U-boats would have met certain destruction, had it still been necessary for them to surface periodically, for a few hours, to charge batteries. The problem presented by the

Schnorchel U-boat has been the chief concern of surface craft, whose main difficulty has been that of distinguishing between a bottomed U-boat and a wreck. An extensive survey of wrecks in British waters helped considerably in solving this problem.

Schnorchel enabled U-boats to operate in inshore waters, but it did not enable them to achieve any significant results. Operational results during the last two years of the war indicated that the standard U-boat, with or without Schnorchel, could not operate successfully against Allied antisubmarine measures. It is important to realize, however, that the U-boat war was not decisively ended in May 1945. Germany had a fleet of about 120 Type XXI U-boats ready to start operations and was developing the Type XXVI U-boat. It is difficult to say whether the high submerged speed would have restored the advantage to the U-boats and would have enabled them to inflict considerable damage on Allied shipping without suffering excessive losses.

7.3.2 From the Allies' Point of View

The Allied and neutral nations lost about 111,000 gross tons of merchant shipping each month, from all causes, during this period. This was the lowest average monthly loss of the war and about 25 per cent less than in the previous period. The construction of new merchant shipping averaged about 850,000 gross tons a month, slightly less than in the previous period. Consequently, there was a net gain of about 736,000 gross tons of shipping each month, or a total increase during this period of about 8,000,000 gross tons in the amount of shipping available.

Of the 111,000 gross tons of shipping lost monthly from all causes, about 84,000 gross tons were lost as a result of enemy action. U-boats accounted for 56,000 gross tons a month, or about 67 per cent of the total lost as a result of enemy action. Monthly losses to enemy mines rose to 15,000 gross tons (18 per cent of enemy action total) as Allied shipping moved close to the shores of Europe after the invasion. Losses to enemy aircraft dropped to 8000 gross tons (9 per cent of enemy action total) a month. The other 5000 gross tons (6 per cent of enemy action total) sunk monthly were lost as a result of surface craft attack and other enemy action.

By the end of this period, Allied armies had overrun Germany, and the surrender came on May 8, 1945. The Allies had defeated the U-boats in 1943 and had succeeded in keeping them ineffective thereafter. It was both an offensive and defensive victory as the average U-boat's lifetime at sea in the Atlantic was only three months and it sank only about one-half ship before it itself was sunk. The Allies were not able, however, to destroy the enemy's U-boat fleet without invasion, as the enemy's construction program had been able to replace all losses.

The war seems to have demonstrated that the standard U-boat could not operate on the surface against strong Allied air power. It should be remembered, however, that the U-boats did not operate, to any large extent, with a reliable radar or search receiver that could detect Allied planes at long range. Denied the surface of the sea, the standard U-boat, with limited submerged speed and endurance, could not operate effectively against strongly escorted Allied convoys.

The German solution to this problem was the development of the Type XXI and Type XXVI U-boats, which had much higher submerged speed and endurance and could operate underseas entirely. These U-boats would be relatively as safe from air attack as were the standard Schnorchel U-boats and would be much safer from surface craft attack, due to their high submerged speeds. They would be much more effective against convoyed shipping as their high speed would enable them to approach and keep up with Allied convoys without surfacing. We cannot determine without extensive trials and exercises with high submerged speed U-boats just how much more effective than the standard types they would be. We cannot now determine quantitatively whether they would be 50 per cent better, or ten times as good. From the history of World War II, however, we may conclude that these new U-boats would *have* to be about eight times as effective in sinking ships and about four times as safe at sea as were the Schnorchel U-boats in the last period, in order to achieve the same results as were achieved by the U-boats during their peak period, January 1942 through September 1942.

Chapter 8

SUMMARY OF ANTISUBMARINE WARFARE WORLD WAR II

8.1 OVERALL RESULTS

The opening hours of the war saw the U-boats already in position astride the approaches to the United Kingdom. Their aim throughout the war was to sever the flow of merchant shipping to and from Great Britain, and in the attempt the battle was carried halfway around the world. The U-boats held the initiative from the beginning until their disastrous defeat in the summer of 1943. Thereafter all their efforts were futile, and U-boat warfare, old style, was at an impasse when the war ended. What the enemy might have accomplished with the new U-boats having high submerged speed is conjectural, but there can be no doubt that they would have been a serious menace.

The actual achievements of the German, Italian, and Japanese U-boats during the war resulted in the Allies' loss of 2753 ships[a] of 14,557,000 gross tons. The enemy also suffered considerable losses at sea. It is estimated that 735 German, 79 Italian, and 99 Japanese U-boats were sunk. A total of about 1500 U-boats were built by the enemy, however, to achieve these results.

There were, therefore, about three Allied merchant vessels sunk by U-boats for each U-boat sunk, about two merchant vessels sunk for each U-boat built. In addition, the Allies were forced to maintain a large and costly antisubmarine effort which diverted their attention from other phases of the war. In these terms the U-boat war was a profitable one for the enemy, even though the U-boats were ultimately defeated. If German U-boat operations only were considered, this conclusion would be greatly strengthened. During the period prior to June 1943 they were, of course, unquestionably successful, whereas subsequent operations were an equally complete success for the Allies.

[a] The figures given in this summary are based on CNO records as of November 19, 1945. They do not agree exactly with figures given in other chapters which were prepared earlier. Assessments of attacks, in particular, have been changed somewhat on the basis of intelligence gained from German sources after the German surrender. As is shown in Appendix I, however, the earlier assessments as they existed at the end of the war were in good general agreement with German records of submarine losses and therefore provide a fairly reliable basis for the discussion given in the other chapters.

8.2 MAJOR DEVELOPMENTS

The beginning of the war saw an immediate campaign of unrestricted U-boat warfare. The British had anticipated such a development and put a previously planned convoy system in operation within a few days. The scale of effort was small, however, as there were only a small number of U-boats at sea, and the antisubmarine craft available to the Allies could give only very weak escort to the convoys.

The U-boats concentrated their forces in the vicinity of Britain, making their attacks in daylight from periscope depth. Their tactics were highly aggressive, and each U-boat scored heavily against Allied shipping. As a result they exposed themselves to counterattack by British surface craft, whose Asdic-directed attacks proved to be much more effective than the Germans were expecting. Surprised and confused by the success of British escorts, the U-boats devoted most of their attention to independent ships and those in convoy were relatively safe, even though weakly escorted.

In June of 1940 France fell to the German Army. The resulting worsening of the British strategical situation had a direct effect on the U-boat war. In the first place the threat of a seaborne invasion of England confined large numbers of British air and surface craft to the east coast anti-invasion patrols and diverted them from antisubmarine duties. In addition, the acquisition of bases on the Bay of Biscay cut down on the transit time of the U-boats and allowed them to extend their operations farther into the Atlantic.

As a result of the effective counterattacks suffered by submerged U-boats, the Germans introduced a radical change of tactics. They began to attack on the surface at night, a procedure that was characteristic of them during most of the war. They capitalized on the weakness of British escorts and made many of

the attacks on convoys, usually trailing the convoy until darkness, then coming in trimmed down on the surface for the attack, and retiring on the surface at high speed.

This method was highly successful, and bold individual attacks rolled up large tonnages to the U-boats' credit. The risks were proportionately high, however. By such tactics the outstanding U-boat aces, Prien, Kretschmer, and Schepke, each amassed totals of over 200,000 gross tons, but all three were eventually sunk in March 1941.

One of the most significant countermeasures to these surfaced attacks was the introduction of radar; a makeshift aircraft set was first fitted to escorts in November 1940. Its effectiveness was not great, however, during this early period. Various improvements in the convoy system were made by the British, including the formation of escort groups, Admiralty control of routing, and a wide dispersion of convoy routes. As a result, U-boats had greater difficulty in attacking convoys.

Early in 1941 the results of Germany's U-boat construction program began to be felt. In 1939 the Germans had only a small U-boat fleet, since their hopes were for a short war. When the possibility of a long struggle with Britain became apparent, building of U-boats was given high priority. They were commissioned at a rate of about 20 a month starting in 1941. There was a corresponding increase in U-boat personnel which, of course, resulted in a widespread lowering in their general experience and capability. This was accentuated by the loss of some of the best trained crews.

In the summer of 1941, therefore, the bold tactics of individual night surfaced attacks on convoys were modified. The policy of wolf pack attacks came into use in an attempt to overwhelm the convoy escorts. The procedure was for the U-boat first contacting a convoy to withhold attack, trailing the convoy and homing other U-boats to the scene so that a number could join in the attack, thus capitalizing to the full on the opportunity and reducing the danger to the attacking U-boats. Complementary to this policy was a general movement of U-boats to the west and south in an effort to find independent ships. This movement also gave freedom from the growing air cover in the vicinity of Britain.

As a result of these changes, the British were forced to adopt complete end to end escort of transatlantic convoys. They were aided in this effort both by the German attack on Russia in June 1941 which ended the threat of invasion of England and released craft for antisubmarine operations, and by the entry of the U. S. Navy in convoy operations in September. Despite the great increase in number of U-boats at sea, Allied losses of merchant vessels did not increase.

Another change introduced by the British during 1941 was to have a profound effect on the antisubmarine war, in this case the contribution made by aircraft. Air patrol had been effective in harassing the U-boats from the beginning, but very few successful attacks were made for lack of suitable weapons. The need for a depth bomb exploding at shallow depths was finally realized, and a 25-foot depth setting came into use. With this minor change aircraft eventually became the equal of surface craft as killers of U-boats.

With the U. S. entry in the war at the end of 1941 the scope of U-boat operations expanded rapidly. The Germans had a large and rapidly growing U-boat fleet, so that they were able to launch a full-scale offensive against the weakly protected shipping in U. S. coastal waters. They were at first able to choose and sink their victims virtually unimpeded, and Allied losses reached catastrophic size, 140 ships of 698,000 gross tons in June 1942, for example. Defenses were organized, however, which forced an eventual withdrawal of the U-boats. With the introduction of convoying in Eastern Sea Frontier in May, losses in that area were reduced, while those in Gulf Sea Frontier soared. U-boat successes there were short lived, though the Caribbean remained a soft spot throughout the summer of 1942. Nevertheless the continued extension of convoying and air patrol drove the U-boats out of the coastal areas by fall, and they then returned to the North Atlantic.

During this period U-boat activity in the Eastern Atlantic was at a standstill. Consequently British forces were free to begin a counteroffensive against U-boats in transit from their bases to the operating areas in the Western Atlantic. Coastal Command aircraft patrolling the Bay of Biscay with radar and searchlights inflicted considerable damage on the U-boats during the summer, until countered by German search-receiver development.

As a direct effort to make up the heavy shipping losses, the Allies started an intensive building program during 1942. Despite all their efforts, however, U-boats sank ships faster than they were built until about the end of the year.

In October it was evident that the U-boats were returning to the North Atlantic in force. Attacks on transatlantic convoys were their objective, and they operated in the mid-ocean gap which could not be reached by land-based air patrol. This gave them freedom to operate on the surface and gather very large wolf packs—often ten or more and occasionally as many as 30 to 40. A concerted attack of this sort often led to breaks in the escort formation and disorganization of the defense.

Nevertheless the vast convoys for the North African invasion made their way from Britain without serious losses because of the complete air coverage provided for them. Routine trade convoys were less fortunate as the tonnage lost topped 700,000 in November. Against a U-boat fleet which was able to maintain about 100 U-boats at sea, even the more efficient escorts which were fitted with S-band radar were inadequate. Heavy losses continued during the winter, mostly in the North Atlantic, but also in other widespread areas where diversionary U-boats were operating.

In the spring of 1943 the convoy defenses were bolstered by a limited amount of aircraft patrol in the mid-ocean gap, which proved to be extraordinarily effective. A small number of VLR aircraft became available in March, and the USS *Bogue* (CVE) also sailed in support of the convoys. Considerable numbers of U-boats were sunk, but they continued to attack in force until early May when they were driven off from ONS 5 in the decisive convoy battle of the war. After May 17 no ships were sunk in the North Atlantic for some time.

While aircraft were thus distinguishing themselves in the defense of convoys, the Coastal Command offensive against transit U-boats was also bearing fruit. S-band radar was introduced early in 1943, and the number of sightings and attacks soared. During May, 37 U-boats were sunk in the Atlantic, 11 of them in the Bay of Biscay. The success of these operations continued until the end of the summer.

By July the U-boats had dispersed to try to find a soft spot in Allied defenses. They failed completely, and found themselves attacked even in mid-ocean by CVE-based aircraft. In Atlantic waters a total of 34 U-boats were sunk, mostly by aircraft. The result of such disastrous losses was a complete defeat of the U-boats, in which they gave up aggressive surfaced operations and submerged during daylight hours to avoid aircraft. Ultra-conservative tactics were employed in crossing the Bay of Biscay.

Having thus lost their mobility, the U-boats accomplished nothing until September and October when they attempted to make a come-back against the North Atlantic convoys by employing acoustic homing torpedoes against the escorts. They were beaten off with heavy losses—22 U-boats sunk during October in operations against convoys in order to sink three merchant vessels and one escort. An attempt to attack the convoys between the United Kingdom and Gibraltar was then made, but it was also frustrated and the U-boats forced into a completely defensive position.

For the rest of the winter they adopted a policy of maximum submergence, designed to give them safety from Allied attack. Virtually no ships were sunk. The number of U-boats at sea declined markedly, and every effort was made to develop an effective search receiver for S-band radar to give them immunity from detection by the Allies.

It was not until the invasion of Normandy in June 1944 that the U-boats showed any signs of aggressive action. Their effort to attack shipping in the English Channel was short-lived, however, as heavy air and surface patrols prevented them from achieving any success. They soon abandoned the surface in favor of Schnorchel operation which gave them virtual immunity from detection by aircraft. By lying on the bottom they were able to utilize the poor sound conditions and frequent wrecks to gain considerable safety from Asdic. Operating in this way limited successes against shipping in British coastal waters were achieved during the summer, while sinkings of U-boats became less and less frequent.

In August and September the U-boats withdrew from the Biscay bases to Norway, and then settled down to a small scale offensive around Britain. They met with some success at first, but by the spring of 1945 Allied surface craft had learned to deal with them under those conditions, and the Allied victories on land deprived them of bases and shore facilities. Their only chance for regaining the upper hand was the new high submerged speed U-boat, Type XXI, but due to production difficulties and the general German collapse none of them made an operational patrol against the Allies.

With the German surrender in May 1945, U-boat warfare was to all intents and purposes ended. Japanese U-boats caused the Allies no serious concern during the remainder of World War II.

TABLE 1. Average Monthly Shipping Losses and Construction of Allied and Neutral Nations.
(By period and cause of loss and in thousands of gross tons.)

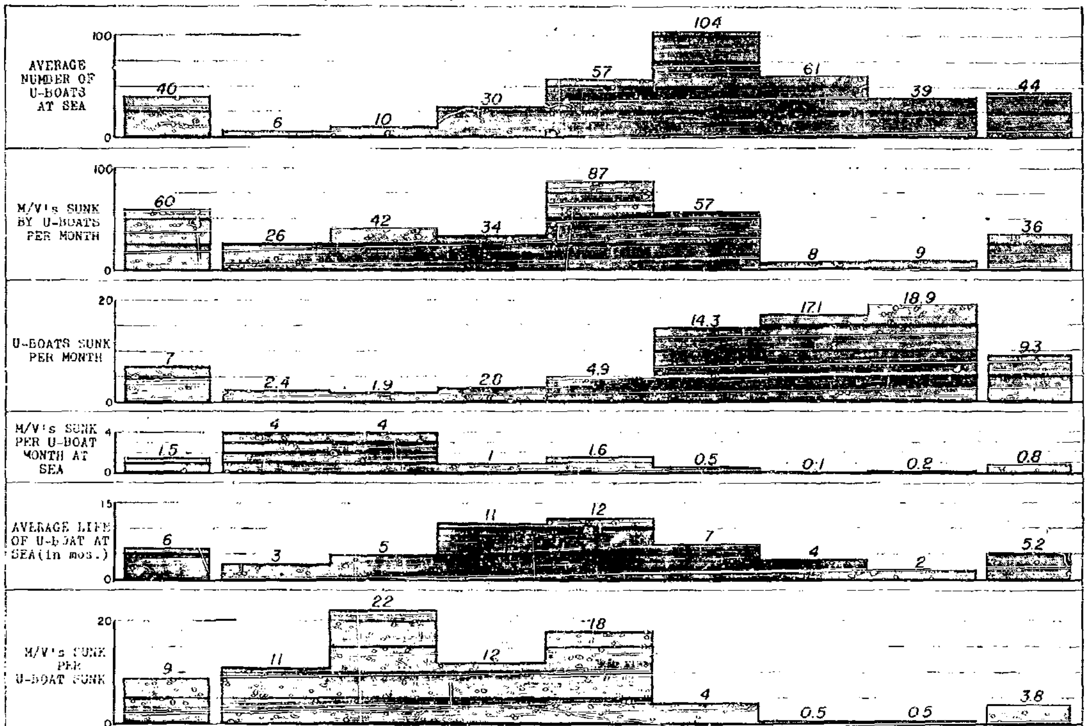
Cause	Period I Sept 39 June 40	Period II July 40 Mar 41	Period III Apr 41 Dec 41	Period IV Jan 42 Sept 42	Period V Oct 42 June 43	Period VI July 43 May 44	Period VII June 44 Apr 45	World War II Sept 39 Apr 45
Sunk by U-boats	106	224	175	508	394	105	57	214
" " aircraft	29	64	76	70	24	35	8	41
" " ships	14	87	17	10	7	4	2	23
" " mines	58	27	20	11	9	5	15	20
" " other enemy action	16	5	34	26	5	2	3	12
Total sunk by enemy action	223	404	322	655	436	151	85	310
Sunk by marine casualty	58	52	40	49	55	32	39	46
Total losses all causes	281	456	362	704	491	183	124	356
New construction	57	114	175	515	1026	1160	850	580
Net monthly *loss*	*224*	*342*	*187*	*189*	......	......	......	......
or *gain*	......	......	......	......	535	977	726	224
Shipping available in million gross tons	40.0	37.8	34.7	33.0	34.3	36.1	46.9	55.0

TABLE 2. Average number of U-boats sunk monthly. World-wide by periods and cause of sinking.

Cause	Period I Sept 39 June 40	Period II July 40 Mar 41	Period III Apr 41 Dec 41	Period IV Jan 42 Sept 42	Period V Oct 42 June 43	Period VI July 43 May 44	Period VII June 44 Apr 45	World War II Sept 39 Apr 45
Sunk by surface craft	2.1	1.7	3.0	3.6	7.2	7.5	8.8	5.0
" " S/C & A/C	0.1	0.3	0.2	0.9	1.2	2.4	1.4	0.9
" " aircraft	0.3	0.2	0.1	2.2	9.3	11.3	10.8	5.4
" " submarine	0.2	0.3	0.1	1.3	1.4	1.3	1.5	1.0
" " other or unknown causes	0.5	0.6	0.7	0.4	0.8	0.8	2.6	1.0
Total sunk	3.2	3.1	4.7	8.4	19.9	23.9	24.4	13.0

TABLE 3. Approximate German U-boat position.
(Ocean going U-boats only, 500 tons or more.)

Period		At start of period	Con-structed	Sunk	At end of period
I	Sept 39 June 40	30	15	23	22
II	July 40 Mar 41	22	45	13	54
III	Apr 41 Dec 41	54	174	28	200
IV	Jan 42 Sept 42	200	200	50	350
V	Oct 42 June 43	350	178	142	385
VI	July 43 May 44	385	250	245	400
VII	June 44 Apr 45	400	180	234	350



PERIOD	Period I. [illegible]	Period II. [illegible]	Period III. [illegible]	Period IV. Apr 1941– Dec 1941	Period V. Jan 1942– Sep 1942	Period VI. Oct 1942– Jun 1943	Period VII. Jul 1943– May 1944	Period VIII Jun 1944– Apr 1945	TOTAL WORLD WAR II Sep 1939– Apr 1945
	[illegible] M/V's sunk [illegible] [illegible] [illegible] A/C generally ineffective against U/B's.	[illegible] [illegible] [illegible] [illegible] electric torpedo (no wake). Allied S/C use asdic successfully	[illegible] [illegible] [illegible] [illegible] [illegible] U/B "Aces" lost in March 1941.	[illegible] [illegible] [illegible] [illegible] U.S. escorts sail with convoys in September 1941. Drop in effectiveness of U/B's due to rapid expansion of U/B personnel. U.S. enters war in December 1941.	U/B's [illegible] to E. coast of U.S. to attack M/V's. Large [illegible] peak in June 1942; [illegible] ships sunk by U/B's. Extensive convoying [illegible] July 1942. [illegible] depth setting on A/C depth charges. U/B's driven away from east coast of U.S.	U/B's attack N. Atlantic convoys in "GAP". Large wolf packs [illegible] [illegible] A/C and escort carriers [illegible] "GAP". S band radar used on A/C in Spring of 1943. A/C attacks much more effective. U/B's badly beaten in attacks on convoy "ONS-5" in March 1943. U/B's withdraw from N. Atlantic.	U/B's disperse, attack supposed weak spots in S. Atlantic. U/B's stay on surface and fight back against A/C. A/C inflict "heavy" losses on U/B's U/B's forced to adopt maximum submergence. U/B's lose offensive power as a result of loss of mobility. U/B's use acoustic torpedo and GSR for S-band radar.	U/B's use Schnorchel to protect themselves against A/C. U/B's operate mainly in "Invasion Area" near England. U/B's use bottoming tactics in shallow water. U/B's lose French bases, move to Norway. U/B's still ineffective, due to lack of mobility. Allied S/C (using Squid and Hedgehog in addition to depth charges) inflict heavy losses on Schnorchel U/B's.	

FIGURE 1. U-boat and antisubmarine operations for the seven periods of World War II.

8.3

TABLES AND CHARTS

The outstanding statistical facts of the antisubmarine war are summarized in the following tables and charts:

1. Figure 1 presents figures measuring the magnitude and effectiveness of U-boat and antisubmarine operations for the seven periods of World War II. The "remarks" attached explain the outstanding characteristics of each period.
2. Table 1 presents Allied shipping losses due to various causes and gains through construction for each period.
3. Figure 2—summarizes the information of Table 1 in graphical form.
4. Table 2 presents the average number of U-boats sunk monthly by cause for each period.
5. Figure 3 summarizes the information of Table 2 in graphical form.
6. Table 3—presents German U-boat losses and gains through construction for each period.
7. Table 4—presents total shipping losses and U-boat sinkings for each period.
8. Table 5 gives the effectiveness of Allied attacks by aircraft and surface craft on U-boats in the Atlantic and Mediterranean for each period.

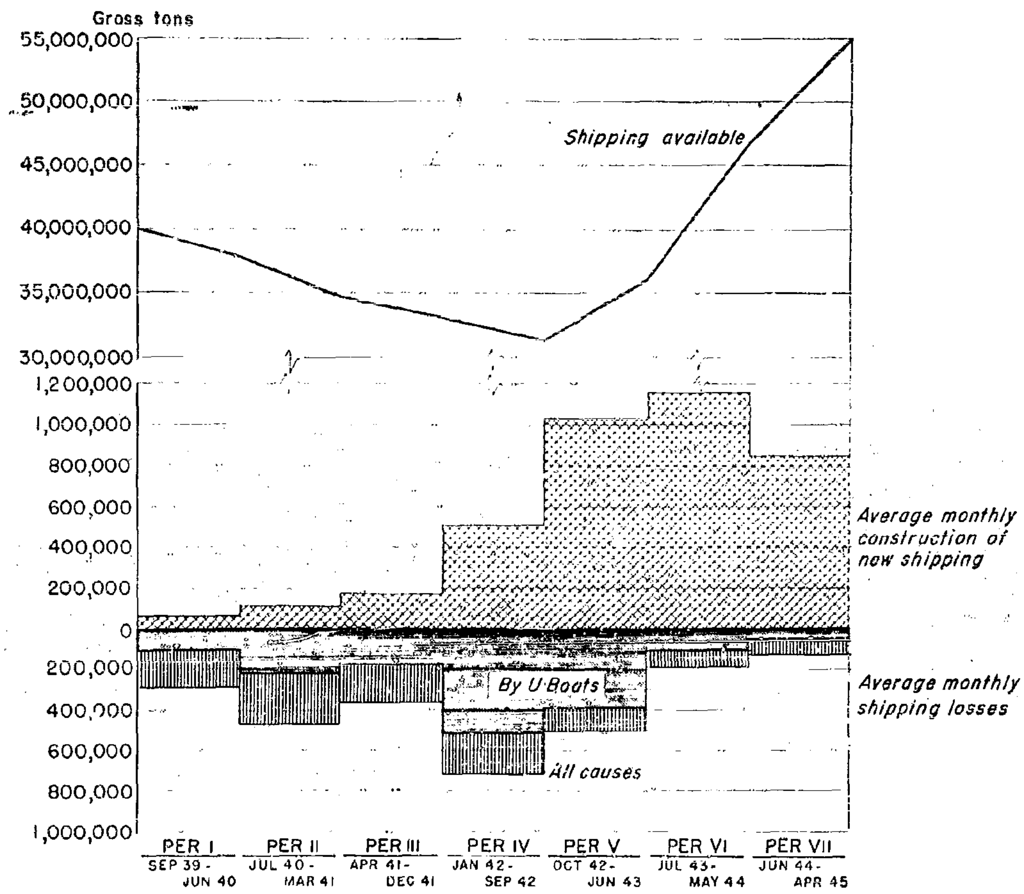


FIGURE 2. Status of Allied merchant fleet during World War II.

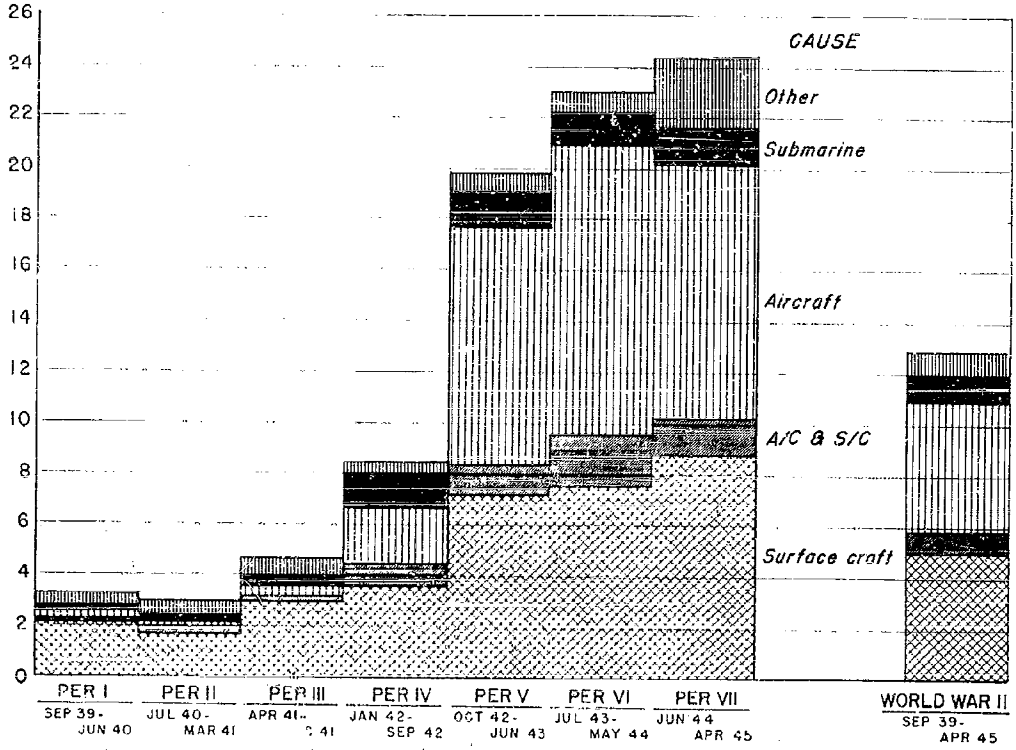


FIGURE 3. Monthly U-boat sinkings by period and cause of sinking.

TABLE 1. Shipping sunk by U-boat and U-boats sunk, by period (world wide).

Period		Ships sunk by U-boat: Number	Ships sunk by U-boat: 1,000 gross tons	U-boats sunk: German	U-boats sunk: Italian	U-boats sunk: Japanese	U-boats sunk: Total
I	Sept 39–June 40	256	1,058	23	9	...	32
II	July 40–Mar 41	379	2,020	13	15	...	28
III	Apr 41–Dec 41	325	1,580	28	14	...	42
IV	Jan 42–Sept 42	878	4,575	50	15	11	76
V	Oct 42–June 43	603	3,546	142	16	18	180*
VI	July 43–May 44	192	1,150	215	10	27	252
VII	June 44–Apr 45	117	618	234	...	35	269
VIII	May 45–Aug 45	3	10	28	...	8	36
Total	World War II	2,753	14,557	733	79	99	915*

* Includes 4 Vichy French U-boats.

TABLE 5. Quality of Allied attacks on U-boats.
(By period — in Atlantic and Mediterranean.)

Period		Aircraft: Percent resulting in at least Some damage	Aircraft: Percent resulting in at least Sinking of U-B	Surface Craft: Percent resulting in at least Some damage	Surface Craft: Percent resulting in at least Sinking of U-B
I	Sept 39–June 40	40	1	Satisfactory data are not available for this early period.	
II	July 40–Mar 41	40	2½		
III	Apr 41–Dec 41	25	2½		
IV	Jan 42–Sept 42	20	2	15	5
V	Oct 42–June 43	25	10	25	10
VI	July 43–May 44	40	25	30	20
VII	June 44–Apr 45	35	18	35	30

PART II

ANTISUBMARINE MEASURES AND THEIR EFFECTIVENESS

FROM THE HISTORICAL summary of operations against submarines during World War II presented in Part I, many conclusions concerning the proper strategy and tactics of antisubmarine warfare [ASW] can be drawn. The most important of these will be discussed in the following chapters and substantiated by quantitative data from Operations Research Group studies.

Most conclusions have to do with specific problems of tactics, for example, weapons for attacks, proper tactics for search, or methods of protecting convoys. These are all part of a general picture which involves the overall purpose of antisubmarine warfare and the various methods available for accomplishing that purpose.

It is already evident from Part I that the aim of ASW is not simply the destruction of unfriendly submarines. If it were possible to sink all enemy submarines, the mission of ASW would, of course, be accomplished, but the forces available have never been sufficient to do this, for a number of reasons. The submarine is a small and elusive object in a large ocean and consequently very hard to find. When found, it is a tough and inaccessible object to attack. As long as the enemy is able to build and launch submarines, he can keep some of them at sea, and even the highly effective Allied antisubmarine effort in World War II did not greatly diminish the size of the German U-boat fleet but merely checked its growth.

Antisubmarine warfare must be thought of as a part of a complex overall military strategy whose final aim is to eliminate the enemy's ability to wage war. This must ultimately be done by seizing or destroying the military or economic war machine—administration, transportation, men, equipment, or production facilities—by striking at the heart of the enemy, not merely nibbling piecemeal at his periphery, or by convincing him of an ability to do so. When possible it is most efficient to ignore the periphery and proceed directly to the ultimate objective. This is the philosophy underlying the blitzkrieg and war of encirclement.

The aim of ASW is to ensure the use of the oceans necessary for military operations intended to bring about the defeat of the enemy. It is an auxiliary operation, necessary, but not sufficient, for overall success. In this sense, then, the actual aim of ASW is negative, to prevent enemy submarines from accomplishing *their* aim.

The first step in this analysis of the subject is to outline the value of submarine operations to the enemy. The objective of ASW is to reduce this value to a minimum, and its general strategy is planned accordingly.

SUBMARINE OPERATIONS

The peculiar value of the submarine among naval craft is its ability to operate in enemy-held waters. Even when surfaced, a submarine is a small target for visual or radar detection. When submerged, it is completely concealed except for detection by underwater sound, whose ranges are short and unreliable.[a] As a result, the submarine can operate in regions forbidden to surface craft because of enemy patrol. In these regions aircraft operations are often impossible because the regions are beyond the range of aircraft. Thus the submarine is the primary, and often the only, craft for carrying out operations at a long distance from base in the areas of the enemy's main strength.

Numerous types of operation may be involved. The aim of some may be to gather information that can be gained only by an excursion into enemy territory. In this class are routine scouting and weather reporting missions and also those involving the landing of agents. Some are transport missions to supply isolated units which cannot be reached by other means. The main mission of the submarine, however, is offensive—to attack the enemy's ships, both combatant and merchant. Past experience has shown that the most valuable submarine activity has been that of attacking merchant shipping, and antisubmarine warfare is of urgent concern on this account.

Man being a terrestrial animal, the oceans are valuable to him only as a means of transportation from one piece of land to another or as a barrier between

[a] Visual detection of a submerged submarine is possible only in very rare cases. Magnetic detection is effective only at very short ranges, much shorter than those of underwater sound.

them. Control of the ocean secures this use to the controller and denies it to his enemy. While an antishipping offensive by submarine does not give control of the ocean, it serves to deny free use to the enemy, and in this negative sense the submarine force may accomplish quite complete control. To the extent that this is done and the enemy prevented or hindered from transporting necessary cargoes, the submarine offensive makes a major contribution to the progress of the war.

In the submarine's antishipping offensive three things must be accomplished: achieving contacts on ships, approach to within torpedo range, and final attack. The first of these is essentially a search problem of the kind discussed in Volume 2B, *Search and Screening*, with submarine as searching craft. Detection may be made by visual, radar, or sonar means. Visual detection has had the largest range and sonar the shortest, as a rule, though the ranges depend on conditions. Visual detection, for instance, will be ineffective on a dark night, and sonar ineffective in poor sound conditions.

Since the submarine's speed is low, it is not a very efficient searching craft and must operate in regions of high shipping density to make a large number of contacts. To select the high density areas a knowledge of the expected positions of enemy ships is required, which may be based on intelligence information or gained locally by coordination between submarines. The "wolf pack" tactics of German U boats accomplished this by homing many submarines to each contact. Once a single U boat made contact, the information was used to permit others to achieve contact as well.

When contact has been made, the submarine must approach to within torpedo range before an attack can be launched. If the submarine's speed is greater than that of the target, the approach is not very difficult, and practically all ships contacted may be attacked. However, if the submarine is forced to operate submerged (or if the target is very fast), approach is only possible from positions ahead of the target, and slight errors in the approach may result in failure to achieve the proper position.

Once firing position is reached, torpedoes are fired. Their chance of success depends on the accuracy of the torpedo fire and on the physical characteristics of the torpedo used.

The primary aim of ASW is to reduce the effectiveness with which the submarines carry out these steps, and the success of an antisubmarine effort is to be assessed in these terms. Antisubmarine warfare is not an end in itself, but merely a means of ensuring that the ability to use the ocean for transportation is maintained at the best level possible.

ANTISUBMARINE MEASURES

Some antisubmarine measures are specifically intended to hinder the submarine in carrying out a particular phase of its antishipping operations. Evasive routing of convoys to avoid known submarine positions is useful solely in reducing the submarine's chance of contacting the convoys. If all the ships could always dodge the submarines, the latters' effectiveness would be much reduced. Such a procedure would slow the ships down appreciably, however, so that the submarine effort would not be entirely wasted. On the other hand, most measures designed to combat submarines serve a multiple purpose. Maintaining aircraft patrol in the vicinity of a convoy not only may lead to sightings of submarines, thus permitting evasion by the convoy, but these aircraft also force submarines to dive, thus hindering them in their efforts to track a convoy and approach it. Finally, an occasional aircraft may be fortunate enough to attack a submarine and sink it. The overall value of any measure must be based on all the ways in which it serves to frustrate the submarine.

Most obvious among the measures designed to reduce the submarine's rate of contacting ships is evasive routing. If the submarine positions are fairly well known, they can be avoided and the density of shipping in their vicinity greatly reduced. Convoying is another measure which, in effect, reduces the submarine contact rate. If there are n ships in each convoy, on the average, the submarine contacts only about $1/n$ as many convoys as it would ships. Since n may be made as large as 50 to 100, the resulting gain is considerable. Patrol by aircraft also serves to reduce the contact rate, as indicated earlier, by forcing the submarine to spend a large fraction of its time submerged. This reduces its detection range and interferes with the formation of wolf packs. In a less direct way, both surface and aircraft patrols and hunter-killer operations have the same effect. A concentration of offensive operations in areas of high density of shipping serves to force the submarines out of these areas and to make them operate where their chances of contacting ships are not so good. The apparent aim

of such an offensive is to sink U-boats, but its chief effect may be to force them to adopt less profitable tactics, and this effect continues to be valuable even if sinkings of U-boats be reduced to a negligible level.

The methods of hindering submarine approach consist of various forms of escort, both for convoys and single ships. Aerial escort tends to force the submarines to submerge and thus restricts their mobility, making it impossible for them to trail the convoy or to overtake it from the flanks or rear and reach a position ahead from which attack can be made. Even if the submarine is ahead of the convoy when she contacts it, a submerged approach is more difficult than one carried out partially on the surface and is more likely to result in errors.

If the submarine boldly elects to stay on the surface for approach to the convoy, it is very likely that it will be detected and attacked in the process, which experience is almost certain to eliminate any possibility of successful offensive action on its part. Correspondingly, surface craft escorts interfere with the later stages of the approach. Having to try to avoid them complicates the submarine's problem, but, if it fails to do so, it is likely to be detected and counterattacked before reaching torpedo-firing position. The submarine's problem can be made still more difficult by use of the highest possible speed of ship and by zigzag, when possible.

Attempts to interfere with the submarine's final attack, after it has reached firing position, have not been very successful in the past. To some extent the mere presence of surface escorts may constitute such interference. Zigzagging reduces the accuracy of torpedo fire somewhat. A maneuverable ship may turn to avoid the torpedo if the ship has sufficient warning, and special torpedo detectors may be devised to aid in doing so. Antitorpedo nets and other devices can be streamed to intercept the torpedo. All these are examples of devices and tactics designed to reduce the effectiveness of the submarine torpedo fire.

Supplementing these essentially defensive methods of interfering with the submarine's accomplishment of its objective is the offensive phase of ASW. The most certain way of preventing a submarine from sinking ships is to sink it first. In this sense, sinking a submarine is equivalent to saving as many ships as it would normally sink during the remainder of its operational lifetime. If, for example, the average submarine makes a total of ten operational patrols and sinks two ships in each, sinking the submarine saves an average of ten ships, because the submarine is likely to be about half through its normal life when sunk.[b] In addition to this direct diminution of the submarine fleet, the sinkings tend to reduce the state of training and experience of the submarine crews. If, for example, the rate of sinking can be kept high enough to give the submarine (or crew member) an expected life at sea of only four patrols, there will be very few men available with the experience of, say, ten patrols. The resulting dearth of experienced personnel is a handicap very difficult to assess, but unquestionably of considerable practical importance. Only a fraction of the value of offensive operations can be represented by the numerical decrement achieved in the enemy's submarine fleet.

There is normally an appreciable effect upon morale as well. The effectiveness of submarine operations cannot be divorced from the skill and determination of the submarine force's personnel. By selectively eliminating experienced men, the high rate of loss reduces not only their overall skill but also their determination. The submarine's chance of being sunk if it endeavors to attack a certain convoy, for example, cannot but bear a greater importance to its crew than to the theoretical strategist. The submarine crews will accordingly avoid operations which involve high losses to themselves, even though theoretically profitable, unless their psychology includes a definite suicidal tendency.

From this brief outline it is evident that ASW involves a great many different aspects. The following chapters will discuss a number of specific problems in order to illustrate the general principles involved. The subjects for discussion have been chosen on a dual basis: first, for their importance in antisubmarine strategy and tactics, and, second, for their interest as examples of the methods of Operations Research.

[b] This type of comparison can be made most clearly on the basis of sinking rates, as in Chapter 13.

Chapter 9

SAFETY OF INDEPENDENT SHIPPING

As was pointed out in Part I (page 2), the submarine's problem is one of first contacting a ship, then approaching to a good torpedo-firing position, and finally securing a torpedo hit. It is appropriate to break down an analysis of measures designed to increase the safety of shipping into the same general categories.

9.1 REDUCTION IN SUBMARINE'S ABILITY TO CONTACT SHIPS

In the first place, anything which can be done to reduce the number of ships contacted by each submarine will increase the safety of the ships. Consider, for example, a ship making a trip between two points through an ocean infested with submarines.

There are D submarines per sq mile in the ocean, each of which has a sweep rate of Q sq miles per hour.[a] The length of the ship's track is l miles and its speed v. Then the expected number of times that submarines will contact the ship is

$$N_a = DQ\frac{l}{v}. \tag{1}$$

To make N_a small, D, Q, or l/v must be decreased. These factors will be considered in turn.

9.1.1 Reduction in Submarine Density

One method of reducing the submarine density to which the ship is exposed is to avoid regions in which submarines are concentrated. If it is possible to choose between a route along which there are many submarines and one where there are few, the latter is certainly the better. When a fairly reliable estimate of submarine positions is available, much can be done by evasive routing to reduce contacts, but such information is by no means always available. If this information is not available, a wide dispersion of shipping routes can be employed, forcing the enemy to deploy his forces in the same way, instead of permitting him to concentrate them against a well-defined shipping lane.

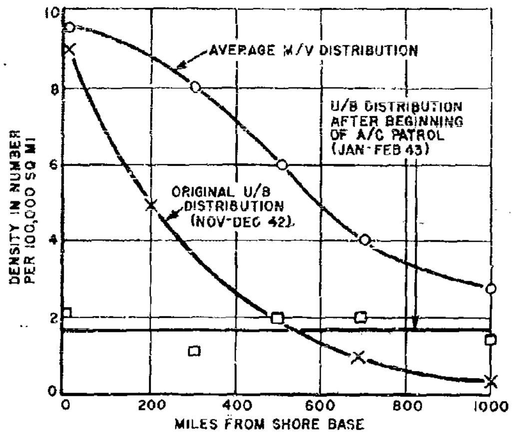


Figure 1. Effect of aircraft flying on the distribution of U-boats in Gibraltar-Morocco area.

In an indirect way, offensive antisubmarine operations serve to reduce D, first, by sinking submarines and thus reducing their number at sea, and, second, by preventing them from concentrating in the most profitable areas. Aircraft patrols frequently can be used to force U-boats out of the regions of the highest concentration of ships. As an example of this process, a graph of U-boat density in the Gibraltar-Morocco region is shown in Figure 1.

Immediately after the Allied landings in North Africa, the U-boats were concentrated close to shore in the region of highest density of merchant ships. Almost immediately, however, aircraft patrol forced them to give up the inshore concentration, which had, no doubt, resulted from a special effort to break up the invasion. The effect of this change in U-boat distribution on their expected number of contacts on ships can be estimated very simply. In any particular region, the expected number of contacts is

$$N = D_{U\text{-}B} \times A \times Q \times D_{M/V} \tag{2}$$

where A = area of region, $D_{U\text{-}B}$ = density of U-boats, and $D_{M/V}$ = density of merchant vessels. This expected number must be calculated separately for

[a] The sweep rate Q is defined in Volume 2B, *Search and Screening*. Q gives the effective area which the searcher is able to inspect completely in a unit of time.

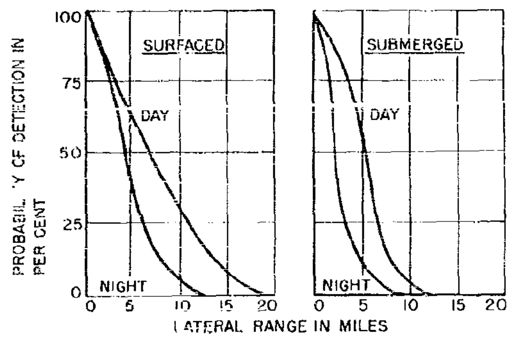


FIGURE 2. Lateral range curves, submarine detection of merchant ships.

each region and summed. If this is done and a value for Q of 100 sq miles per hour is taken as typical of a submarine search rate for merchant ships, then we would expect about 60 contacts per month by U-boats on merchant ships before flying had forced them out, and 30 contacts per month afterwards. It would be reasonable to conclude that the flying involved[b] had cut the danger to ships approximately in half.

9.1.2 Reduction in Submarine Sweep Rate

To some extent, aircraft patrol may fail to drive U-boats out of an area as described above and merely force them to spend most of their time submerged. This also serves to make ships safer because it reduces the submarine's sweep rate. The primary reason for the reduction is the decrease in the range of detection, though the drop in submarine speed also has some effect. The submerged submarine is relatively blind compared with a surfaced one, since visual detection must be through periscope and also since radar cannot be used very conveniently.

Operational data on the magnitude of these effects can be derived from the first contact ranges reported by U. S. submarines. From these data the lateral range curves of Figure 2 are plotted. The assumption has been made that there is a definite range at which contact will be made for each time that a submarine meets a ship, though these ranges vary widely from one occasion to the next.[c] The area under these curves gives s the sweep width, the values being as given in Table 1.

TABLE 1. Submarine sweep width in searching for merchant ships.

	Day	Night	Average
Surfaced (miles)	14.5	9.1	12
Submerged (miles)	9.8	4.2	7

The overall effect of forcing the submarine to submerge appears to be a reduction of 40 per cent or so in the sweep width. We can, then, consider half the sweep width to be the effective range of contact, which would be 6 miles surfaced and 3.5 miles submerged. If submarines remained fixed in the ocean, there would be a proportional reduction in the number of ships contacted by the submarine, but since the surfaced submarine is able to add something to its search capabilities by patrolling at about 10 knots, the speed effect must also be taken into account, though it proves to be rather small.

This speed effect is treated in Chapter 1 of Volume 2B, *Search and Screening*. The result is expressed in equation (5) of that chapter, which allows us to write the search rate Q of equation (1) explicitly as

$$Q = \frac{N_0}{N} = \frac{4R}{\pi}(u+v)\int_0^{\pi/2}\sqrt{1-\sin^2\delta\sin^2\psi}\,d\psi;$$

$$\sin\delta = \frac{2\sqrt{uv}}{u+v}, \tag{3}$$

where

Q = sweep rate,
N_0 = expected number of contacts per unit time,
N = number of ships per square mile,
R = effective range of contact,
u = submarine speed,
v = merchant vessel speed.

From equation (3) we can calculate Q, using tables to determine values of the elliptic integral involved. With the assumption that the merchant ships involved make 10 knots, the surfaced submarine 10 knots, and the submerged submarine 3 knots, the results are as presented in Table 2.

The net conclusion is, therefore, that a submerged submarine has been able to contact only about half as many ships as a surfaced submarine and that antisubmarine patrol which forces submarines to sub-

[b] Total flying hours were: November, 933; December, 1833; January, 2167; February, 2120.

[c] See Chapter 2 of Volume 2B, *Search and Screening*, for a complete exposition of contact phenomena.

TABLE 2. Sweep rate of submarine in contacting merchant ships.

	Submarine speed (u)	Range of Contact (R)	Sweep rate (Q)
Surfaced	10 kt	6 miles	150 sq mi/hr
Submerged	3 kt	3.5 miles	70 sq mi/hr

merge most of the time has an appreciable effect in reducing contacts.

Another line along which effort might reasonably be expended to reduce the submarine's contact rate is camouflage. Since, however, it is by no means easy to devise a camouflage which is effective in this sense under all the varied conditions met with in practice, relatively little has been done, and operational data on the subject are not available.

9.1.3 Reduction in Ship's Time at Sea

The factor l/v in equation (1) is simply the time the ship spends in the dangerous region. To keep this time small, the track length l should be made as short as possible and high ship speed used. The advantages of high ship speed in this connection are offset, however, by an increase in Q with ship speed. The most important consideration is length of ship's track in dangerous waters.

9.2 REDUCTION IN SUBMARINE'S ABILITY TO APPROACH SHIPS

When the submarine has made a contact, it must still make an approach to torpedo-firing position before launching an attack, and it is by no means certain that it will be able to do so. In a typical period only 41 per cent of the independent merchant vessels contacted by United States submarines were attacked. Some of the remaining 59 per cent were not worth attacking, but many were not attacked because the submarine was unable to close to the desired position for launching a torpedo. The quantitative importance of the approach problem is made more evident by an analysis of the effect of merchant vessel speed on the safety of independent ships, based on Allied losses to German U-boats.

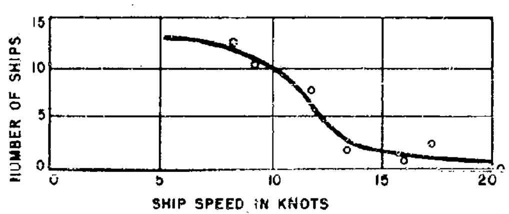


FIGURE 3. Ships sunk per million miles of track in a U-boat density of 1 per million square miles, as a function of ship speed.

9.2.1 The Effect of Ship Speed on Submarine Approach

In order to study the effect of speed, it is necessary to assign the ships to speed classes and then determine the number of ships sunk in each class and the overall exposure of each class to submarines. This overall exposure must take into account both the total distance traveled by ships of each class and the density of U-boats along the ships' courses, as indicated by equation (1).

In order to do this a study was made in which the Atlantic was separated into areas. In each area the mileage traveled by independents of different speed classes and the average density of U-boats were taken month by month. A ship which sails 2000 miles in waters with one U-boat per million sq miles is exposed to about the same risk as one traveling 1000 miles in waters with two U-boats per million sq miles. Hence, the exposure for each speed class is given by the product of the mileage and the U-boat density. This was done for seven speed classes, covering a period of 4 months and four areas.

The number of casualties per unit of exposure is a measure of the safety of the speed class in question, and this is plotted in Figure 3 as a function of speed. The sharp decrease in sinkings at speeds between 10 and 15 knots is very obvious. In order to explain this result the following analysis of submarine approach methods is required.

If a ship is sighted in a favorable position, the U-boat may approach either surfaced or submerged and attack directly. If the U-boat is not in a favorable position, it has to estimate course and speed and follow the ship until it can close the range or get into position ahead for a submerged approach. The direct attack may be called Method A, the attack following a chase, Method B. Since Method B provides a good opportunity for tracking and obtaining torpedo-firing data, it is frequently used, a typical procedure being to track until dark and then attack.

Method B requires that the U-boat be able to overtake the ship, namely, that the ship speed be not greater than about 15 knots (14 knots appears to be the critical speed in Figure 3). Method A, on the other hand, may be used against ships of any speed, though the number of times the U-boat is in favorable position will decrease as the speed of the ship increases. This decrease certainly does not account for the sharp rise in the curve of Figure 5, which is due to the advent of attacks made by Method B. A diagram is helpful in making clear the significance of these two methods.

In Figure 4, the submerged approach zone and effective contact range are plotted. The shaded area drawn to 2000 yd on either side of the ship is taken as a rough approximation to the zone in which a submarine has a good chance of scoring a torpedo hit. Suppose that a submarine which makes contact while ahead of the ship in the submerged approach zone can make an attack by Method A with average chance of success k. Then the crosshatched line gives the sweep width for Method A attacks. For a very fast ship, the sweep width is approximately 2 miles, and increases to about 12 miles for very slow ships as the limiting approach angle increases. Then the expected number of Method A attacks per million miles of track in a U-boat density of one per million square miles is given by the length of this line and the expected number of sinkings is k times as great.

Assuming that submarine speed (under water) 5 knots and that $k = 0.20$, the dotted line in Figure 5 is a rough graph of expected sinkings by Method A. For ships of speeds of 15 knots or greater, all observed sinkings are accounted for, but many additional ships of speeds less than 15 knots were sunk, presumably by Method B. Either the submarine is enabled

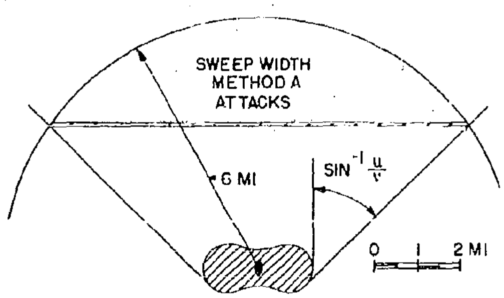


FIGURE 4. Submarine approach zone.

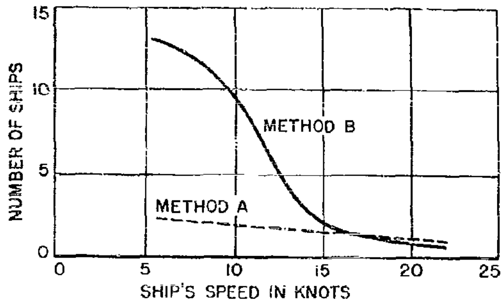


FIGURE 5. Ships sunk per million miles of track in a U-boat density of 1 per million sq miles.

to track the ship and wait for a very favorable opportunity to attack or is able to try again after a failure, in order to attain a high eventual level of success.

For purposes of comparison, calculate the number of ships that would be sunk if every ship contacted by U-boats were sunk, using equation (1). If we take the example previously discussed, a 10-knot ship and assume that the U-boats are surfaced, then conditions corresponding to Figure 5 are

$$D = 1/1{,}000{,}000,$$
$$l = 1{,}000{,}000,$$
$$v = 10,$$
$$Q = 150.$$

We have

$$N = 1/1{,}000{,}000 \times 150 \times 1{,}000{,}000/10$$
$$= 15 \text{ ships contacted per million miles of track.}$$

Thus we would expect 15 ships to be contacted, whereas Figure 5 shows 10 sunk under these conditions. This seems like a rather high percentage, but it should be remembered that the conditions are on the whole rather favorable to the U-boat — a slow ship, unescorted, with little or no air patrol. A faster ship would be very considerably safer, though the number of times it is contacted per mile of track would not be greatly different.

To summarize, then, there are three important speed classes.

1. High-speed ships — sufficiently fast that the submarine cannot track or overtake them. The sinkings are low and not greatly dependent upon speed, though the additional speed of the ship clearly makes the submarine's problem increasingly difficult.

2. Low-speed ships — so slow that the submarine can track and overtake without difficulty. Sink-

TABLE 3. Independent merchant vessel losses, Caribbean Sea Frontier (July 1942–Feb 1943).

Month	Average No. of U-boats	Average No. of independent M/V	Independent M/V sunk	U-boat sinking rate	(2-month)	Flying hr from Trinidad
July 1942	5.1	11.7	16	210	140	....
Aug	6.4	12.6	6	60		2,100
Sept	9.0	13.7	20	140	115	5,000
Oct	8.6	11.4	9	89		5,000
Nov	5.1	13.6	9	105	100	4,700
Dec	4.0	11.1	5	90		4,400
Jan 1943	3.0	11.3	0	0	0	5,100
Feb	1.8	10.0	0	0		5,000

ings are approximately ten times as great as in the high speed case and are not critically dependent on speed.

3. Intermediate-speed ships — for which there is an abrupt transition from the conditions of class 2 to class 1 and whose losses depend strongly on speed.

The critical speed is one approximately equal to the surfaced speed of the submarine. A change in submarine speed would result in a corresponding change in the curves of Figures 4 and 5. With the U-boat capabilities of World War II, the critical importance of speed in the 10- to 14-knot range is obvious. Any measure, such as frequent dry docking to clean the bottom, which might give an extra knot or two of speed in this range would be well worth while for a ship destined to sail independently through submarine waters.

9.2.2 The Effect of Aircraft Patrol on Submarine Approach

The important role played by surfaced pursuit and tracking on the part of the submarine makes it evident that any measure which keeps the submarine submerged a considerable part of the time will greatly reduce its chance of converting a contact into a sinking. Consequently, aircraft patrol, which tends to force the submarine down, might be expected to eliminate Method B attacks and greatly increase the safety of independent ships. The reduction in sinking rate indicated for 10-knot ships by Figure 5 is 83 per cent; that is, about one-sixth as many ships would be lost as when surfaced tracking was possible.

Operational data showing a clear comparison between surfaced and submerged operation are difficult to obtain without great differences in time and place. In addition, the advent of aircraft flying is normally accompanied by the start of convoying, and the effects of each are difficult to distinguish. For example, the start of convoying would normally increase the average speed of independent ships since the slow ships would be put in convoy. As a result, independent ships would appear to become safer. The type of result which may be obtained is shown in Table 3, which presents data from the Caribbean Sea Frontier during the fall of 1942. The area considered includes the first 120 miles from shore in the Caribbean Sea Frontier West and involves primarily action in the vicinity of Trinidad. As a rough measure of the aircraft flying involved, data on flying in the Trinidad sector are used. The U-boat sinking rate (in sq miles per hour) is given by the following equation.

Sinking rate

$$= \frac{(\text{M/V sunk})(\text{Area involved})}{(\text{M/V's in area}) \times (\text{U/B's in area}) \times (\text{hr/mo})} \tag{4}$$

In this case the area involved is about 600,000 sq miles.

From a consideration of the first and last 2-month periods, it is apparent that an increase in flying has taken place, accompanied by a decrease in the sinking rate. But it is not evident whether the former was indeed the cause of the latter, and, if so, whether the Method A and Method B considerations involved had anything to do with it. When the sinking rate and flying are plotted graphically as in Figure 6, it appears that there was a lag of several months between the rise in the flying curve and the decrease in sinking rate. At the time the increase in flying was

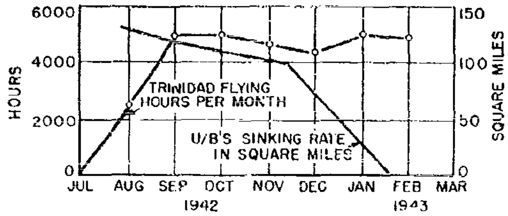


FIGURE 6. Sinking rate and flying, by months (Caribbean Sea Frontier, West).

made, the U-boat sinking rate dropped only slightly. This suggests that the flying did not cause the drop in sinking rate directly, but that the increased antisubmarine effort eventually (about January 1943) caused the U-boats to abandon their offensive in that area and adopt more conservative tactics. As is evident from Table 3, they actually started to withdraw from the area in November and were practically all gone by February. The drop in sinking rate probably means that the few remaining made much less of an effort to attack ships than they had done some months before, rather than that aircraft flying directly prevented them from attacking by keeping them submerged.

The flying was not, in fact, sufficient to do so, as can be seen from an elementary calculation in which we estimate the amount of flying that would be required to prevent surfaced tracking by submarines.

If for example, it is assumed that to deny a submarine surfaced operation it must see a plane and be forced to dive at least twice a day, the number of flying hours required to produce this effect can be calculated. A sort of sweep rate can be assigned to the aircraft by supposing that all submarines within 5 miles of the track are forced to dive, and no others (probably a rather generous figure). Then the aircraft must cover the area involved 60 times during the month, a total of 60 x 600,000 = 36,000,000 sq miles covered. But the aircraft's sweep rate is 2 x 5 x 125 sq miles per hour, assuming an aircraft speed of 125 knots. Hence, the total number of flying hours required is

$$\text{Flying hours} = \frac{60 \times 600,000}{2 \times 5 \times 125} = 29,000 \text{ per month.}$$

The actual flying recorded is not, strictly, the total amount in the area under consideration, but the total from Trinidad. Some of it was outside the area, and some other flying was done in the area. Nevertheless, the total flying in the area considered was certainly a good deal less than 29,000 hours per month and could not be expected to eliminate surfaced operation of U-boats.

Sufficient flying to eliminate surfaced operation can ordinarily be accomplished only in a very limited area. In the vicinity of the British Isles, however, such a situation existed during the last months of World War II. U-boats operated totally submerged, using Schnorchel in the most heavily patrolled inshore waters. In view of the densities of U-boats and ships involved, however, they did not make very many sinkings. Many factors besides aircraft patrol were important, and a detailed analysis of the situation would be extremely complicated. It is mentioned merely as evidence that submarines may at times go to the extreme of totally submerged operation.

9.2.3 Effect of Zigzag on Submarine Approach

With respect to the submarine's approach problem the importance of high ship speed and of aircraft patrol to enforce submerged operation have been discussed. Both of these are effective antisubmarine measures in that they make it difficult for the submarine to carry out an approach to the ship. Another measure with the same aim is worth considering: the zigzag. By making fairly radical turns at irregular intervals, the ships can make it more difficult for the submarine to approach to a good firing position and to secure good torpedo-firing data. The net result is that the submarine will tend to be forced to fire from a poorer position with poorer accuracy and will therefore have less chance of securing a hit. At present, however, quantitative data on the effect of zigzagging are not available.

9.3 REDUCTION IN EFFECTIVENESS OF TORPEDO FIRE

Once the submarine has reached position and fired its torpedoes, there are still certain defensive measures which can be taken to reduce sinkings. Torpedo detectors have been devised to warn of the torpedo's approach, thus permitting a turn to avoid it, but they have not been effective on merchant ships. Ships should be built so as to be as likely as possible to stay afloat when hit. Special protective devices

such as antitorpedo nets may be employed. Because of their extensive use, operational data on their effectiveness are of considerable interest.

To January 1, 1944, 25 ships fitted with Admiralty Net Defense [AND] nets were reported to have been torpedoed, with the results given in Table 4.

TABLE 4. Results of torpedoes fired at ships fitted with antitorpedo nets.

	Sunk	Damaged	Undamaged
Nets not in use when attacked	9	3	9
Nets in use	1	3	3
Use of nets unknown	3	0	0

Of the ships not using nets, 75 per cent of those fired at were sunk, but with nets streamed only 40 per cent fired at were lost. The chance of being sunk is still about half what it would be without nets, because some torpedoes either go through the nets or hit at unprotected ends of the ship. Table 4 above also indicates that about half the torpedoings occurred when nets were not streamed, so that the ultimate effect is that ships fitted with nets suffer about three-quarters the losses that they would sustain without the nets.

These are the overall results, of course, and depend on the manner in which the nets are used. In the period considered, many of the ships were in convoy and streamed nets only when attack was considered likely. Bad weather is also a cause for nonstreaming of nets. This factor enters into the overall usefulness of nets.

A serious drawback of net defense is the attendant reduction in speed when nets are streamed. This amounts to about 17 per cent. For a 14-knot ship, the reduction in speed to 11½ knots increases the danger to the ship by a factor of about 3½, if the ship is sailing independently, according to Figure 3. This increase more than overbalances the 50 per cent reduction afforded by the nets; consequently, their use would not be desirable in this case. If, however, the original speed were only 10 knots, reduction to 8 knots would not seriously increase the danger, and nets would be most desirable for use in submarine waters.

9.4 SUMMARY

To summarize, then, there are a number of defensive measures which may be taken to reduce sinkings of independent ships. Most of them are effective because they make it more difficult for the submarine to carry out its approach and attack. The overall effectiveness of these measures is limited, however, and the most successful defensive measure has been the use of escorted convoys, which will now be discussed.

Chapter 10

CONVOYING AND ESCORT OF SHIPPING

THE PRIMARY advantage of a convoy system is the concentration of defense that it allows. Since it is impossible to provide an escort for every individual ship at sea, ships must sail in groups so that each group may be adequately escorted. A secondary advantage is the reduction in number of units at sea for the submarine to contact, since the convoy becomes the unit instead of the individual ship. It is convenient to analyze the gain achieved from convoying in the same three steps as were discussed in the last chapter: contacts made by the enemy, his ability to make an approach, and his chance of sinking ships once firing position is attained.

10.1 THE GAIN IN SAFETY BY CONVOYING

10.1.1 Reduction in Number of Contacts Made by Submarines

The institution of the convoy system results in a considerable reduction in the number of contacts made by submarines. The number of sightings made depends on the number of units present to be sighted. Clearly, 100 independent ships sailing in a given area represent 100 opportunities for sighting, while the same number of ships in two convoys of 50 ships each offer only two opportunities for sighting. Each sighting, however, gives 50 targets and is accordingly of increased value, as will appear from subsequent sections. This effect tends to neutralize the benefit derived from grouping, but only to a small extent. In addition, an increased range of detection tends to increase the number of convoys that are contacted. Although the range of detection on a 50-ship convoy is by no means 50 times that on a single ship, it is appreciably greater, and some consideration of the increase is necessary.

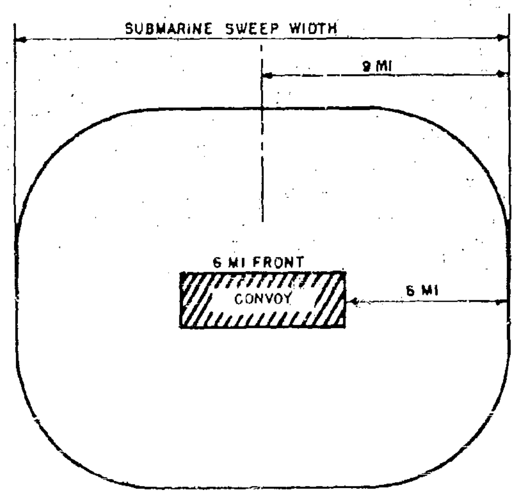


FIGURE 1. Submarine sweep width on convoy.

Visual sightings, if made on masts or superstructure, will be made at about the same range on convoys as on independent vessels. A large convoy covers a sufficiently large area to increase the sweep rate about 50 per cent, as shown in Figure 1, but this is not a serious increase. Submarines often sight ships by smoke, however, which may be seen at distances up to 40 miles. A single ship may make smoke only a small fraction of the time, but usually there is at least one ship in a convoy which is smoking, and smoke becomes very much more important. If b is the fraction of time that each ship smokes, R_1 the range on a ship itself, R_2 the range on the smoke, and n the number of ships in convoy, then

$$\text{Fraction of time convoy smokes} = 1 - (1 - b)^n$$

Average range on convoy

$$= (1 - b)^n R_1 + [1 - (1 - b)^n] R_2$$

$$= R_2 - (1 - b)^n (R_2 - R_1). \tag{1}$$

For convoys of as many as 50 ships, $(1 - b)^n$ is so small that the sighting range is approximately R_2, the range of detecting smoke. For a plausible set of values ($R_1 = 4$ miles; $R_2 = 24$ miles; $b = 0.10$), equation (1) gives the following average ranges.

Single ship	6 miles
8-ship convoy	11 miles
64-ship convoy	23 miles

The submarine's radar will generally detect a convoy at a longer range than a single ship, because the convoy presents a larger reflecting target. Since, how-

ever, the intensity of the radar echo decreases very rapidly with increasing range to the target (normally as $1/r^4$ or faster), the increase in range is not very great. Operational data giving ranges of submarine radar on large convoys are not available. U. S. submarines have obtained ranges about 35 per cent longer on convoys of about 3 to 4 ships than on single ships. Aircraft radar ranges on large Atlantic convoys have been only 10 to 25 per cent greater than on single ships. It would not be expected, therefore, that grouping of ships in convoy would cause a serious increase in the range of radar detection.

The range of sonar detection will be appreciably increased. The intensity of sound produced by a convoy of n ships is about n times that of a single ship. On this basis it has been estimated that the range on a 50-ship convoy under favorable listening conditions would be about three times that on a single ship. Under less favorable conditions the ratio would be smaller.

In order to estimate the overall change in range of detection, it is necessary to determine the relative importance of the different methods. In general, visual detection ranks first, because of long range and ease of identification, radar second, and sonar third. During a period near the end of World War II, for instance, United States submarines made about 800 contacts by visual detection, 300 by radar, and 50 by sonar. German U-boats have not had as effective search radar as United States submarines, so that the importance of radar in U-boat operations has been much less. These figures would depend a great deal on submarine tactics: a submarine which spent most of the time submerged would make relatively more sonar contacts. It is thus evident that the contact range increases with an increased number of ships but is by no means proportional to it. A fairly reasonable approximation would be to consider the range as proportional to $n^{1/3}$. Then the expected number of contacts made will depend on two factors: this increased range and the decrease in the number of units at sea to be detected.

$$N_c = N_i \times n^{1/3} \times \frac{1}{n} = \frac{N_i}{n^{2/3}} \tag{2}$$

where

N_c = expected number of contacts on convoys;

N_i = expected number of contacts on same ships sailing independently.

A change from $n = 1$ to $n = 64$ will reduce the number of contacts made on a given number of ships at sea by a factor of 16, according to equation (2).

This gain by convoying is somewhat enhanced by the greater ease of evasive routing of convoys. With a convoy system in operation, there are few units at sea and it is relatively easy to direct them so as to avoid known submarines or concentrations of submarines. This would not be so practical for independent vessels. Their number would be too great, their positions too poorly known, and their communications inadequate. Hence available intelligence concerning submarine dispositions can be utilized most effectively with a convoy system.

The decrease in contacts resulting from a convoy system usually causes the submarines to employ "wolf-pack" tactics, in which any submarine making contact endeavors to inform others in the vicinity and home them to the convoy. For the second and subsequent submarines, the search is no longer at random, and the number of contacts made is increased by their additional knowledge. If half a dozen submarines can be homed to each original contact, the number of contacts made by each is approximately six times as great as without homing. United States submarines operating in groups of about three have made about 1.7 times as many contacts as those hunting independently.

German U-boats have formed wolf packs as large as 10 to 20 for some attacks, though their average size was, no doubt, much smaller. The general procedure was for the first U-boat making contact to report the convoy to U-boat control (and to other U-boats) and then to trail the convoy without attacking, supplying more information concerning the convoy as available, and, when possible, supplying homing signals to aid other U-boats in closing the convoy. On receipt of the contact report, control would direct other U-boats in the vicinity to intercept the convoy and attack it. Thus a group of U-boats would collect in the immediate vicinity of the convoy, each acting more or less independently. When a U-boat was in favorable position, an attack would be launched, and, after a brief retirement, the U-boat would endeavor to get into position again for reattack. This procedure would often be kept up for several days and nights. In this way only a fraction of the total number of U-boats in the wolf pack would be in contact with the convoy at any one time, and only a fraction of them would be actively attacking. Never-

theless, the ability to form a large attacking group when a convoy is sighted is of great importance in convoy battles, and much antisubmarine effort is devoted to preventing tracking and wolf-pack formation.

10.1.2 Submarine Approach to Convoy

When the submarine has made contact with a convoy, an approach to within torpedo-firing position must be made. There are two aspects to the submarine's problem: the natural difficulty of making such an approach, particularly serious when submerged, and the additional difficulty of avoiding detection and counterattack by the convoy's escorts. The typical convoy being large, slow, and unmaneuverable, the latter aspect is usually the more important. Only in the case of a fast convoy which the submarine cannot track or overtake on the surface is there any great difficulty in the approach process when the submarine is unopposed by escorts.

As was seen to be the case for independent ships, speed has an important effect on the safety of convoys. A speed sufficient to prevent tracking and overtaking makes it impossible for the submarine to get into position ahead by an end run, reduces the tracking data which the submarine can obtain, and limits it to one quick approach and attack. In addition, high convoy speed makes it difficult to gather a wolf pack for the attack. The effect of speed cannot readily be broken down for analytical study, and presentation of operational data on the overall effect of speed is deferred until a later section. The detailed evaluation of the effectiveness of escorts, both surface and aircraft, in detecting and preventing the approach of a submarine to a convoy, is discussed in Volume 2B, *Search and Screening*, since the screening problem is simply that of searching for a target known to be trying to approach a certain region. In Volume 2B, Chapters 8 and 9, methods are described for deciding on the optimum screening disposition or plan. Consequently, the problem of making such decisions will not be discussed here. The general method of analysis, however, is as follows.

The convoy is surrounded by a torpedo danger zone which includes all points from which the submarine has a fair chance of hitting one or more ships in the convoy (a chance of 25 per cent or greater, for example). Ahead of this zone is another called the submerged approach zone, bounded by the limiting approach lines on the sides and the submarine's detection radius of the convoy on the front. Any submarine in this zone is considered to be aware of the presence of the convoy and can approach it submerged. To the flanks and rear is the surfaced approach and tracking zone, in which submarines are in contact with the convoy but must remain on the surface to have sufficient speed to approach or track it. (For a fast convoy this zone also has a limiting after-bearing behind which the submarine cannot approach, even on the surface.) These zones are shown in Figure 2.

The primary aims of aircraft escort are two.

1. To force down submarines in the surfaced approach and tracking zone and cause them to lose contact with the convoy; and

2. To detect submarines which would enter the submerged approach zone and prevent them from doing so. The submarines are to be forced down and immobilized so that the convoy may be turned away from the contact and thus avoid the submarine.

A good aircraft escort plan should reduce by at least 50 per cent the number of submarines gaining access to the submerged approach or torpedo danger zones. In addition, tracking and wolf-pack formation are made very much more difficult.

The chief aim of the surface craft screen is to detect submarines in the submerged approach zone and take them under counterattack before they can fire

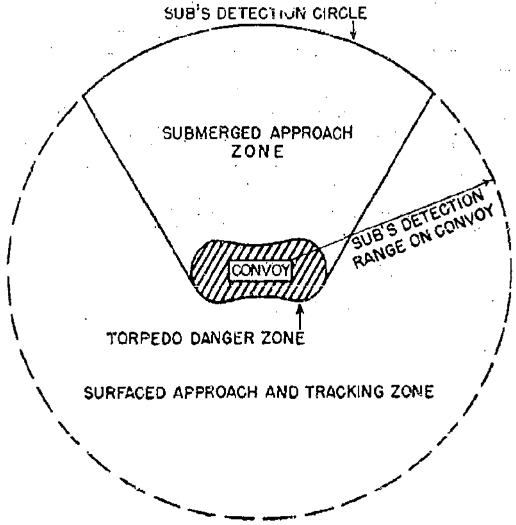


FIGURE 2. Submarine approach zones around a convoy.

torpedoes. In addition, surface craft may take offensive action against submarines first contacted by aircraft and must be prepared to intercept surfaced approach and prevent tracking when air cover is not available. Their effectiveness in the latter role is difficult to estimate. With a normal size convoy, sonar screens may reasonably be expected to intercept 50 to 75 per cent of the approaching submarines, assuming good sonar conditions and a normal number of screening ships.

To compare the safety of a convoy with that of an independent ship on a theoretical basis, all these factors should be taken into account quantitatively. This can be done only in the most approximate sort of way. The aircraft screen should intercept at least 50 per cent of the submarines approaching, and the surface craft at least 50 per cent of those not detected by aircraft. Other things being equal, the submarine would be able to carry through less than one-quarter as many approaches to escorted convoys as to independent ships per hundred initial contacts. The danger of attacking an escorted convoy is great enough to have an important psychological effect, as well. A strong escort may deter the submarine commander from even trying to attack. Actually, the large size and low maneuverability of a convoy certainly simplify the submarine's approach problem somewhat, and it seems probable that the ratio between the fraction of successful approaches on convoys and the fraction on independents would be nearer one-half than one-quarter.

10.1.3 Torpedo Hits Slightly Easier to Achieve on Convoys

Having achieved a firing position, the submarine still has the problem of securing one or more torpedo hits. It is evident that this will be easier with a convoy than with an independent ship, since a large number of targets is presented. In general, the submarine will fire at a particular ship, but may fail to hit it and hit some other ship instead. A detailed discussion of the calculation of the probability of such hits is discussed in connection with the mathematical formulation of the screening problem in Volume 2B, Chapter 8. A typical example will suffice to illustrate the principles involved. Consider the case of a submarine firing into a large convoy from abeam as shown in Figure 3.

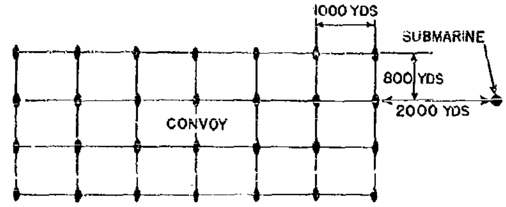


FIGURE 3. Typical convoy disposition.

A torpedo fired from 2000 yd abeam can pass through several columns. If it is fired at random, its probability of encountering a ship while passing through the first column would be $l/800$ where l is the length of a ship in yards. For $l = 140$ yd, the chance of a hit in passing through three columns (5000-yd range torpedo) would be

$$\text{Probability of hit} = 1 - \left(1 - \frac{140}{800}\right)^3$$
$$= 44\%. \tag{3}$$

If a total of four torpedoes is fired, the expected number of hits is $4 \times 0.44 = 1.76$. Since not all hits will cause ships to sink, it is reasonable to estimate that 1 to 1½ ships would be sunk as a result of the attack.[a] This is to be compared with a maximum of one ship in an attack on an independent ship; an average result would probably lie in the range from ½ to 1 ship sunk per attack on an independent. On this basis we would expect the ratio between sinkings per salvo fired at a convoy and sinkings per salvo fired at an independent to be not greater than three to one, and, more likely, about two to one.

It is evident from Figure 3 that the number of ships sunk per salvo will not depend at all critically on the size of convoy. If the submarine uses a torpedo of 5000-yd range, it can penetrate only about three or four columns, so that increase in convoy size to more than four columns causes no further increase in ships sunk per salvo. Only with very long-range torpedoes does this quantity continue to increase after a convoy size of 10 to 20 ships has been reached.[b]

[a] This figure depends on a number of factors, such as type of ship, distance from land, roughness of sea, etc. The experience of United States submarines has been that about 40 per cent of the ships hit by one torpedo sink. This would lead to $1.76 \times 0.40 = 0.71$ ships sunk per salvo. Thus the estimate of 1 to 1½ ships sunk is probably too high, if anything, though it may be about correct for rough weather in mid-Atlantic.

[b] As a corollary it may be concluded that for attack on very large convoys, a long-range torpedo would be very effective because it would have good chances of success when fired into the convoy at random as a browning shot.

TABLE 4. Convoy losses in North Atlantic, August 1942–January 1943.

	Convoys	Ships	Convoys sighted by U-boat	Ships sunk	Per cent convoys sighted	Per cent ships sunk
HX (eastbound 9½ kt)	23	923	8	12	35	1.3
SC (eastbound 7 kt)	24	991	14	45	58	4.6
ON (westbound 9½ kt)	24	897	11	29	46	3.2
ONS (westbound 7 kt)	23	836	11	31	48	3.7

10.1.4 Overall Value of Convoying

From these figures a very rough estimate of the overall gain of safety by convoying can be made. A typical average size of convoy during the Battle of the Atlantic was about 30 ships. Transatlantic convoys were often larger, coastal convoys normally smaller. For the comparison three factors must be taken into account.

1. The ratio of contacts made on convoys to those on independent ships for the same number of ships at sea, which according to equation (2) is given by $(30)^{-2/3}$, i.e., about one-tenth.

2. The relative difficulty of making the approach to firing position. It was estimated that the submarine would be successful about half as often with convoys.

3. The fact that sinkings per chance to fire a salvo are probably about twice as great with large convoys.

The net effect of these factors is:

$$\text{Relative loss in convoy} = \frac{1}{10} \times \frac{1}{2} \times 2 = \frac{1}{10}. \qquad (4)$$

This is a considerable gain in safety and is in reasonable agreement with the observed difference in loss rate given in Part I. The loss per month in convoy was 4 per cent during early 1942 in the United States Strategic Area, while that for independent ships was 20 per cent, a ratio of one to five. This ratio is somewhat less than that estimated in equation (4), which is surprising because equation (4) should give a fairly conservative estimate of the gain involved in convoying. One possible explanation of the discrepancy is the emphasis placed by the Germans on wolf packs, by which the advantages of convoying can be largely neutralized. If a pack of ten submarines were collected on each contact and all were effective, the loss in convoy, based on equation (4) would be the same as for independent ships, rather than one-tenth as great. Thus the operational ratio of one-fifth might be interpreted as implying that the Germans were able to home an extra U-boat to each contact, on the average. In many cases, wolf packs of more than two U-boats were formed, but in many other cases only one U-boat was in contact. The average number of U-boats attacking each contact would be two, which can be compared with the number 1.7 which United States submarines have achieved while operating in groups (of about three).[c]

It may be concluded that there is no irreconcilable difference between our theoretical estimate of the situation and operational data for the period quoted, which data are typical of operational results. This overall agreement confirms the belief that convoying is probably the most effective method of reducing sinkings but does not prove that the foregoing picture of the mechanism by which sinkings are reduced is correct. In order to throw further light on the details of the process, it is necessary to analyze the operational data more carefully and determine the effect of factors such as size and speed of convoy and strength of escort, on the losses of ships from convoy. A number of such studies are discussed in the following section and are correlated with the rough theory given above.

10.2 OPERATIONAL STUDIES OF THE EFFECT OF VARIOUS FACTORS ON THE SAFETY OF SHIPS IN CONVOY

10.2.1 The Effect of Convoy Speed

Speed has a very considerable effect on the safety of independent ships and might therefore be presumed to have a similar effect for convoys. There

[c] A figure analogous to the five to one ratio found for independent versus convoyed ships can be obtained by comparing sinkings before and after convoying in certain regions. The Capetown and Trinidad areas (both regions of high U-boat activity) give ratios of about six to one and ten to one.

have been, however, relatively few convoys of speeds from 10 to 20 knots, in which speed range the outstanding effects are observed with independents.

In order to have for study a large number of convoys with serious exposure to submarines, it is necessary to deal with North Atlantic convoys, whose maximum speed was about 9½ knots. Data on these convoys for the 6-month period from August 1942 through January 1943 are presented in Table 1. During this period 80 to 110 U-boats were operating in the North Atlantic and convoy losses were high.

From Table 1 it can be concluded that (1) the effect of speed in the success of the attacks is quite clear in eastbound and unclear in westbound convoys, and (2) that an effect of speed on sightings may be present but is not strongly indicated. The discrepancy between eastbound and westbound convoys is very striking and makes interpretation of the data difficult.

In an attempt to explain this difference, the routes of a fair sample of convoys (omitting those for ON convoys which traveled very much to the south because of containing a portion bound for Africa) were reconstructed. The mean eastbound and westbound tracks are given in Figure 4. The westbound convoys evidently have traversed a route some 200 to 300 miles south of the mean eastbound route between 20 W and 50 W.

A plausible explanation of the different effects of speed on eastbound and westbound convoys follows: Eastbound convoys being farther north received better air cover since aircraft flew from Iceland. Consequently U-boats operating against them had to spend a larger fraction of their time submerged. The *mean speed* of U-boats is therefore less when attacking

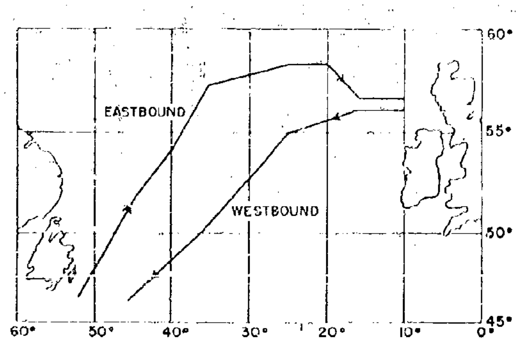


FIGURE 4. Average convoy routes in the North Atlantic, August 1942 through January 1943.

eastbound than westbound convoys. Consequently the increase of speed from 7 to 9½ knots may be a critical range and give large loss reduction for eastbound convoys, though not for westbound. This line of reasoning is confirmed by the fact that aircraft made 10 attacks on U-boats in connection with eastbound convoys and only 5 with westbound.

What is really needed to make the effect of speed quite clear is a set of transatlantic convoys all of which have received approximately the same air cover. Those convoys which travel a southerly route in general are not covered, and, as was shown in Figure 4, this has applied more to westbound than to eastbound convoys. If we eliminate all convoys which make the mid-ocean part of the voyage south of the Great Circle route, the remaining ones should be fairly homogeneous with respect to air cover and should give an indication of the value of speed under those conditions. For this purpose the routes of all transatlantic convoys from October 1942 to early May 1943 were plotted out and those which spent more than half their time (between 15° W and 45° W) south of the Great Circle route eliminated.[d] The remainder is shown in Table 2. Stragglers are included in the figures.

TABLE 2. Losses for convoys on northerly routes.

	Number of convoys	Per cent sighted	Per cent attacked	Ships sunk per convoy sailing
SC and ONS (7 kt)	30	68	43	1.9
HX and ONF (9½ kt)	11	68	11	1.3

[d] For comparison, the data on convoys which spent more than half their time south of the Great Circle are shown.

Losses for convoys on southerly routes.

	Number of convoys	Per cent sighted	Per cent attacked	Ships sunk per convoy sailing
SC and ONS (7 kt)	8	88	88	2.9
HX and ONF (9½ kt)	7	86	86	3.7

The numbers here are small and actually the fast convoys suffered more heavily than the slow. It is of great interest that they were attacked twice as often as those on northerly routes, particularly since the number of U-boats on patrol in the southerly zone was less than a third of the number further north.

TABLE 3. Losses for various sizes of convoys, 1941–1942 (North Atlantic Allied convoys – wolf-pack attacks).

Size of convoy	Number of pack attacks	Average number of ships	Average number of escorts	Average size of U-boat pack	Average number of ships sunk per attack	Ships sunk per U-boat attacking
0–14	1	11	4	4	7	1.8
15–24	8	20.4	6.5	6.5	4.8	0.7
25–34	11	29.7	6.8	5.4	5.6	1.1
35–44	13	38.5	6.4	5.8	6.4	1.1
45–54	7	48.3	6.5	5.2	4.9	0.9
55 and over	2	62.5	8.0	7.5	9.0	1.2

The number of convoys is large enough that the data may be considered significant. There is no difference in the frequency of sightings or attacks, but the number of ships sunk per fast convoy is two thirds of that per slow convoy.

The overall conclusion is that some curve similar to that of Figure 3 in Chapter 9 obtains for convoys, but it is probably displaced in the direction of lower speeds. Air cover tends to cause the critical region of the curve to occur at slower speeds, and the shape of the curve depends on the extent of aircraft escort. The data available are very far from adequate to establish the detailed nature of this curve and its dependence on the air escort provided.

10.2.2 The Effect of Convoy Size

It might very reasonably be claimed that the effect of convoy size is the most important phenomenon associated with convoying; it is, in fact, the essence of convoying, since an independent vessel can be considered to be a convoy of one ship. On the other hand, the presence of escorts might be considered the most important feature of the convoy system, and this feature will be discussed immediately after consideration of the effect of convoy size.

Several studies have been made of the losses suffered by North Atlantic convoys as a function of size and, although the losses were fortunately too small to provide data of unquestionable statistical significance, they lead to some very interesting conclusions. In the first place, data are presented in Table 3 pertaining to convoys which were attacked during 1941–1942 and in which the approximate number of attacking U-boats was known.

The striking feature of Table 3 is the constancy of the figures in the last column. There is certainly no clear tendency for the number of ships sunk to increase with size of convoy. It might be expected that there would be a natural tendency in that direction which would be counterbalanced by an increased strength of escort with the large convoys, but the figures given do not bear out such a contention. For convoys of from 15 to 55 ships the strength of escort was virtually constant, but no appreciable change of sinkings with size of convoy is observed. Hence the earlier theoretical conclusion that increase in convoy size to more than four columns causes no further increase in ships sunk per salvo is borne out by the operational data. A convoy of 15 or more ships is apparently large enough that the number of ships sunk per U-boat attack does not depend on convoy size. Such would not be the case for smaller convoys, where we would expect increased size to be associated with an increase in number (though not in fraction) of ships sunk. Data on small convoys are available from attacks by United States submarines on Japanese convoys. For the period from July 1, 1942, to March 1, 1943, the results are given in Table 4.

TABLE 4. Sinkings from Japanese convoys as a function of size. (By U. S. submarines.)

Size of convoy	Total number of convoys	No. of M/V sunk	M/V sunk per convoy
1	1222	276	0.23
2	409	142	0.36
3	243	103	0.42
4	174	79	0.45
5	98	70	0.71
6	74	47	0.64
7	33	28	0.87
8	27	16	0.60
9	14	13	0.93
10	15	16	1.07
11–12	23	16	0.70
13–14	12	19	1.6
15–20	7	8	1.1

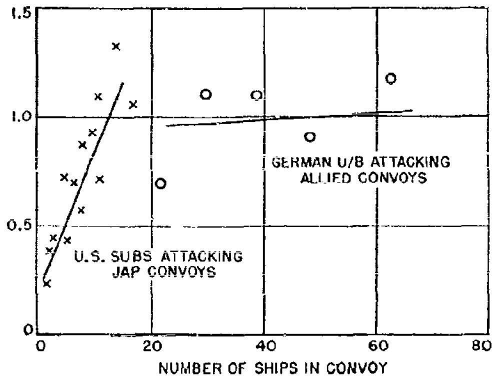


FIGURE 5. Effect of convoy size on ships sunk per submarine attack.

With smaller convoys, there is a definite increase in the number of merchant vessels sunk as the size of convoy increases, which is in accordance with expectations. A comparison of the two sets of data is presented in Figure 5. The two are not directly comparable, since the sizes of convoys involved do not overlap and since the effectiveness of escort in the two cases is undoubtedly different. Nevertheless, the overall picture of a considerable increase for small convoys followed by an inappreciable increase for sizes above 20 ships is quite clear.

So far attention has been devoted to the ships sunk per submarine attack, omitting the frequency with which the attacks occurred. From the data presented it appears that large convoys are much the safest for the individual ships, since the *fraction* of convoyed ships sunk decreases markedly with increasing convoy size. If, however, it were much easier for a submarine to make an attack on a large convoy than on a small one, by virtue of the greater ease of contact and approach, there would not necessarily be any overall gain in the adoption of large convoys. In order to determine whether the preceding results give a true picture of the net effect of changes in convoy size, the problem must be studied in more general terms.

This was done by selecting a fixed region (the United States Strategic Area east of 50° W) in which the U-boat activity was high and by determining the losses suffered by transatlantic convoys in crossing this area as a function of convoy size. A total of 111 convoys were studied; they spent an average of about 7 days in the area. The period covered is from July 1, 1942, to March 31, 1943. A total of 160 ships was sunk. The pertinent data are summarized in Table 5.

TABLE 5. Frequency of attacks and sinkings as a function of convoy size.
(1942–1943, Western North Atlantic.)

Number of merchant vessels	Average number of attack-days* per convoy	Average number of sinkings† per attack-day	Average number of sinkings per convoy	Average number of escorts per convoy
10–29	0.5	1.9	0.9	6.5
30–49	0.4	2.7	1.0	6.4
50–69	0.5	2.3	1.0	6.8

* An attack day is defined as a day on which a sinking occurred.
† Sinkings in convoy only; stragglers are excluded.

Again the losses suffered by the convoys do not depend on size of convoy. On the average, approximately one ship was sunk from each convoy crossing the region, regardless of its size. Since the convoys in the 50 to 69 group were about three times as large as those in the 10 to 29 group, each ship in the large convoys was exposed to only about one-third the danger to which each was exposed in the smaller ones.

10.2.3 The Value of Surface Escorts

An outstanding feature of the convoy system is the provision of protective forces, both surface craft and aircraft. Surface craft will be discussed first. These antisubmarine ships have a number of functions: (1) detection of submerged submarines at the front of the convoy and of surfaced submarines approaching from any bearing, (2) offensive sweeps to harass, locate, and put down submarines in the vicinity which are trying to trail the convoy or get into position ahead of it, and (3) attacks on submarines when opportunity presents. Escort of convoy is more than a matter of defensive screening, and the most successful escort group has been the one which prevents the enemy from ever obtaining the initiative and launching a determined attack on the convoy. The conflict between the group of escorts and an attacking wolf pack is one which cannot be simply described but involves the skillful use of radar, sonar, visual detection, radio direction finding, available intelligence, and weather conditions, and an avoidance of routine and stereotyped tactics. An endeavor to estimate the value of escorts on a theoretical basis

would be a hopeless task, but an interesting indication of their importance can be obtained from operational data.

Numbers corresponding to those of Table 3 are given in Table 6 for 1941-1942 in the North Atlantic.

TABLE 6. Merchant ship losses as a function of escort strength (1941-1942 in North Atlantic).

Escort strength	Number of pack attacks	Mean escort strength	Ships sunk per U-boat in pack
1-4	22	3.4	0.88
5-9	51	6.7	0.75
10-15	75	11.1	0.31

The final column gives the average number of ships sunk in an attack per U-boat present in the attacking wolf pack. This figure is a measure of U-boat success in penetrating the screen and sinking ships. The chief effect of surface escorts might be expected to be in preventing the U-boat from reaching firing position. In very simple terms we can interpret the figures (plotted in Figure 6) in the following way.

1. Assume that in the absence of any escorts the U-boat can make a virtually unopposed approach and sink 1.2 ships. (Earlier it was estimated that a salvo would sink 1 to 1.5 ships.) When escorts are present, their effect is considered to be one of reducing the fraction of cases in which the submarine reaches firing position undetected, but the number of ships sunk *if* it does so is not changed.

2. The effect of each additional escort is to reduce the ships sunk by about 0.075 ship, that is, to reduce the U-boat's chance of penetrating the screen by about 6 per cent. Apparently, 16 escorts would give

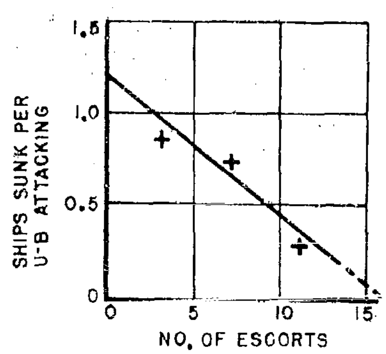


FIGURE 6. Effect of number of escorts on convoy losses.

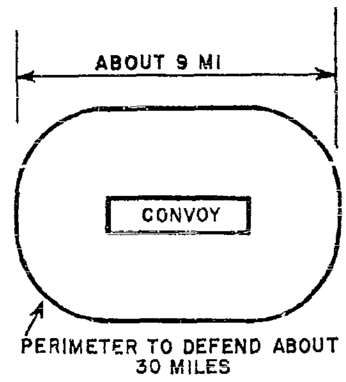


FIGURE 7. Zone to be defended by escorts.

complete protection. During the period under study most attacks were made at night and the sort of perimeter which the escorts had to defend is shown in Figure 7. If 16 escorts are distributed around this perimeter, it can be seen that each one effectively screened about 2 miles of it or, in other words, had an effective detection range of about 1 mile on the U-boats under those conditions (surfaced night attacks predominating; most ships fitted with radar, but not all centimeter type; North Atlantic wolf pack operations).

It is rather surprising that there is no evidence of an upward concavity in the curve of Figure 6. It does not seem likely that even 16 or more escorts could completely prevent submarines from sinking any ships, but it does seem likely that the number of ships sunk would be made very small, perhaps 0.1 or 0.2, for large numbers of escorts. On the other hand, it may be that the presence of a large number of escorts is sufficient to discourage U-boats from aggressively pressing home attacks. Perhaps they would consider it too dangerous to attack a convoy with 15 or more escorts ever to try to do so, even though they might actually have some chance of success. The data available are sufficient only to suggest this question, not to answer it. They do, however, show conclusively that strength of escort played a very important role in determining ship losses.[c]

The figures of Table 6 are given on a per attack

[c] This contrasts strongly with the experience of United States submarines in attacking Japanese convoys, for their ability to sink ships has not been affected by the number of convoy escorts present; the only possible conclusion is that Japanese detection equipment and procedure have been highly ineffective.

basis, however, and do not take into account the frequency of attacks. Since surface escorts are often used for offensive sweeps designed to shake off trailing U-boats and prevent attack, such figures may not be a complete measure of the escort's value. Unfortunately, it is not possible to determine from operational data the ability of the escorts to prevent *attack*. One complicating feature is the tendency to provide more escorts when and where the danger is greatest, which increases the relative number of attacks made on convoys when many escorts were present. Actually the data of Figure 6 may be considered a conservative indication of the value of surface escorts.

10.2.4 The Value of Aircraft Escorts

Similar information on the value of aircraft can be obtained by comparing the losses suffered by aircraft-escorted convoys with those sustained by convoys without such escort. Data are presented in Table 7 for North Atlantic convoys from August to December 1942. Only the days (and nights following) on which U-boats were known to be in contact are included, so that all figures pertain to threatened convoys.

TABLE 7. Ship losses as a function of air escort. (August to December 1942, North Atlantic)

	Number of days	Ships torpedoed	Average number of sorties	Average size of U-boat pack in contact	Ships torpedoed per day
With air cover	38	23	4	4.9	0.60
Without air cover	43	75	0	5.5	1.75

Since the days with and without air escort pertain to the same convoys and are in the same period, with approximately the same size of wolf pack in contact, we can feel quite confident that the difference between 0.60 and 1.75 ships torpedoed per day is actually due to the aircraft escort. The number of ships torpedoed is reduced to about 30 per cent of the value that it would otherwise have by the presence of such escort (an average of four sorties per day staying about 2 hours with the convoy). This figure, of course, applies to convoys encountering wolf packs of surfaced U-boats and must be used with caution. In addition, there is an interrelation between convoy speed and the effect of aircraft escort which was previously noticed in connection with analysis of speed

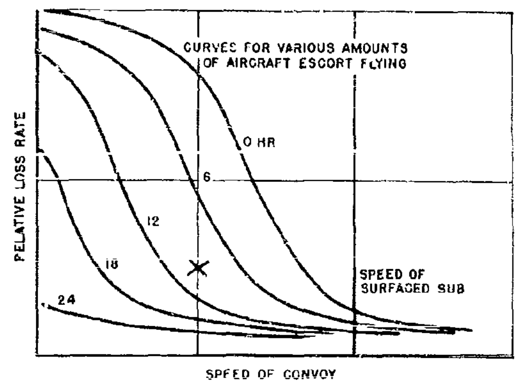


FIGURE 8. Effect of aircraft flying and convoy speed.

effects. Figure 8 is an effort to present the probable form of the relationships.

The curves are drawn for various amounts of aircraft escort flying. The general belief is that the primary effect of aircraft flying is to reduce the speed of convoy for which the submarine can carry out Method B tracking and approach, because it is forced to submerge at least part of the time. If we assume that 24 hours per day aircraft flying will eliminate tracking even for the slowest of convoys, then the curves drawn may be taken as representing 0, 6, 12, 18, and 24 hr of aircraft flying per day. The plotted X corresponds to the data of Table 7 (average speed of convoy about one half surfaced U-boat speed, loss rate reduced to 30 per cent). Since the point is for 8 hr per day of flying and lies suitably enough between the 6 hr and 12-hr curves, the operational data can be considered in agreement with the curves which were sketched in on the basis of very qualitative arguments. It may be concluded that the curves of Figure 8 give a good indication of the effect of aircraft escort and convoy speed on the losses of ships from convoys, but data available are not sufficient to demonstrate their exact nature, and they can be based only on indirect and devious reasoning.

10.3 THE IMPORTANCE OF LARGE CONVOYS

It is evident from the preceding discussion that ships are safest when sailing in large, well-protected convoys. Although this fact may seem trivially obvious, a quantitative estimation of the overall importance of large convoy size is of interest.

For purposes of comparison, consider a situation in which a total of ten ships and one escort are ready to sail each day and calculate the losses for three cases: 30-ship convoys, 60 ship convoys, and 90-ship convoys. A convoy spends 6 days in the dangerous region, and a total of 12 hours per day of flying can be done actually escorting convoys. Convoy speeds are assumed to be one-half the submarine's surfaced speed. The tactical situation is presented in Table 8.

TABLE 8. Comparison of convoy sizes.

	Case I	Case II	Case III
No. of ships in convoy	30	60	90
No. of escorts with convoy	3	6	9
Days between convoys	3	6	9
Convoys in danger area	2	1	$\frac{2}{3}$
Flying hours per convoy day	6	12	18

Correspondingly, a table can be made of the contributions to relative loss rate of each of the factors involved: convoy size, number of escorts, and extent of aircraft flying. This is done in Table 9.

TABLE 9. Relative loss rates.

	Case I	Case II	Case III
Effect of convoy size [Fig. 5 and eq. (2)]	1.00	0.69	0.56
Effect of number of escorts (Fig. 6)	1.00	0.75	0.55
Effect of aircraft flying (Fig. 8)	1.00	0.50	0.30
Overall	1.00	0.26	0.09

Thus it may be concluded that ships in large convoys are very much safer than those in small or medium-sized ones under the conditions of this example. A ship's chance of being sunk in a 90-ship convoy is about one tenth that in a 30-ship convoy. In order to achieve full effectiveness from convoying as a means of protecting ships, it is of utmost importance to make the convoys large and well-defended. There are certain practical limitations to the size of convoy that can be sailed, but these results show that for maximum safety of ships convoys should be made as large as possible, larger, in fact, than they normally have been, even in the Atlantic.

The chief difficulties involved in very large convoys are:

1. Increased difficulty of communications within the convoy. Signals from the commodore's ship must be passed from one ship to another along rows and columns, and the passing of visual signals by merchant ships in a large convoy leaves much to be desired. Ships in convoy maintain radio silence, and a secure system of intraconvoy signaling has never been available. It is possible that the maintenance of radio silence may not be justified when the losses through faulty communication are balanced against the gains due to evasion of U-boats.

2. Decreased maneuverability of convoy. With large convoys turns are difficult in any case and the case of maneuvering is not a critical function of size.

3. Increased number of stragglers. It may be argued that a greater fraction of ships will straggle from large convoys, primarily because of (1) and (2) above, and, since danger to stragglers is high, this may seriously increase the losses suffered by large convoys. Operational data, however, indicate that this effect is not large, probably because the chief reasons for straggling are engine breakdown or similar failures which are in no way related to convoy size.

4. Increased port congestion. To some extent any convoy system crowds harbor facilities, but the difficulty is increased the larger the convoys are. To the extent that ships spend unnecessary days in port, they are not available for carrying cargo and their value is reduced. The turn-around time in port is made up of:

a. Waiting for berths to load and discharge. (This applies mainly to ships handling dry cargo, not to tankers.)

b. Discharging and loading.

c. Waiting in the channel for a convoy to sail.

Period (a) will usually be kept fairly small after the convoy system has operated for a time but may be extended if the size of the convoy is increased above what has been a working average. Period (b) depends on the nature of the cargo and varies between 2 and 20 days, as a rule. Period (c) averages half the time between convoys ("convoy cycle"). Hence, an increase in convoy size will somewhat increase the turn-around time.

The ultimate limitation on convoy size is thus the effect of increased size on the time spent in port and consequent slowing down of the actual transport of goods. If, for example, the average ship spends 10

days at sea and 15 days in port for an average convoy size of 30 ships, but 20 days in port for a convoy size of 90 ships, the increase in convoy size reduces the rate of cargo transport by 20 per cent. This is equivalent, as far as cargo carrying capacity goes, to an immediate sinking of 20 per cent of the ships involved and cannot be tolerated except in cases where the expected number of ships saved by the increase in convoy size is comparably great.

10.4 LIMITATIONS ON CONVOYING

It has been shown that a convoy system greatly increases the safety of ships at sea, especially if convoys are large and well protected. The gain is accompanied, however, by a loss in cargo carrying capacity of the ships available, and convoying is by no means universally desirable. There are two main ways in which convoying slows down cargo transport: the increased time spent in port and a decreased speed of ship which results in increased time spent at sea.

An analysis of United States coastal trade convoys was made, using the ships at sea during June 1943 as a sample. It was found that on the average a convoyed ship spends 43 per cent of its time in port and 57 per cent at sea. Of the time in port, 16 per cent is spent in waiting for convoys to form. Of the time at sea, 19 per cent could be saved by allowing the vessels to proceed independently at their rated loaded speeds. Consequently, if all these ships were routed independently, the same amount of goods could be transported within the shipping system in 69 per cent of the time required with convoys (which were rather small and had a cycle of about 5 days). Hence, the cargo carried by the convoyed ships was only 69 per cent of what could have been carried by them if they had been sailing independently.

Suppose, however, that the ships are routed independently in order to speed transport. The number of ships sunk per month is increased, and fewer ships are available. By the time that 31 per cent of the ships have been sunk, the situation would no longer appear favorable. The cargo carried per month by convoyed ships and independent ships would be as shown in Figure 9. (Loss rates assumed are 1 per cent per month at sea for convoys, 20 per cent for independents; convoyed ships at sea 57 per cent of the time, independents, 67 per cent.) After about 3 months, convoying begins to pay dividends in terms of greater cargo carrying capacity.

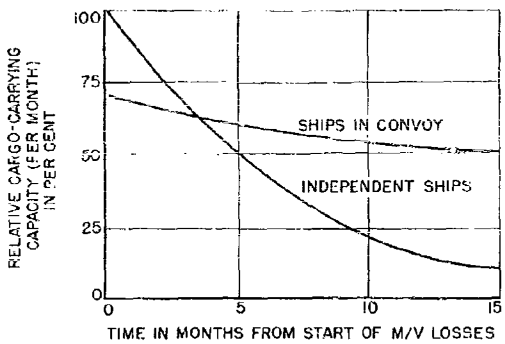


FIGURE 9. Cargo carrying capacity of ships during submarine offensive.

In deciding on the desirability of convoying, however, the total cargo carried is the chief item of interest. After 3 months the independent ships would still have carried more cargo because they had a considerable initial advantage. It would not be until after about 6 or 7 months that the convoyed ships would have the larger total. This total is plotted in Figure 10.

Thus the overall value of convoying in any particular situation depends on how much longer the war is going to last, among all other things. For the conditions represented by Figure 10, independent ships would produce the best result as long as the war was not likely to last more than 7 months.

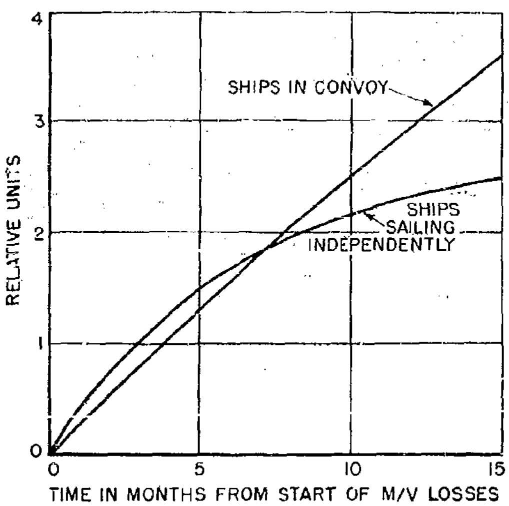


FIGURE 10. Total cargo carried.

whereas convoying would be desirable in a longer war. In addition, the bad effects of failing to convoy in the latter case appear somewhat more serious than the bad effects of convoying when one should not do so, which may be reason for advocating a generally conservative procedure. The overall conclusion is, then, that convoying is a powerful method for protecting ships, but that it should not be applied unless the seriousness of the enemy's submarine offensive and the probable duration of the war justify it. If the danger from submarines is fairly great, then large convoys should be formed.

Chapter 11

ATTACKS BY SURFACE CRAFT

When an antisubmarine ship or aircraft makes contact with a submarine, an attack is normally made in order to sink or damage it. During escort operations, "embarrassing," or "urgent," attacks may also be made whose chief purpose is to frighten the submarine crew and prevent it from pressing home its attack on the convoy. This type of attack will not be considered in the following discussion, since its value is largely psychological and cannot readily be evaluated in quantitative terms. The so-called deliberate attack, on the other hand, aims to destroy the submarine, and this aim can be expressed mathematically. In designing attack weapons and tactics the objective is to make the probability of destruction a maximum. The problems which arise in doing so will now be analyzed.

11.1 GENERAL STATEMENT OF PROBLEM

As is true in the other aspects of antisubmarine warfare [ASW] discussed in the previous chapters, the basic principles of attack are simple to describe. It is only when these principles are examined in more detail that complicated problems arise. So before passing to the details of the attack consider the over-all picture of a surface craft attack against a submarine, first in terms of an *a priori* analysis and then in terms of an *a posteriori* analysis of operational results. These two points of view will also be employed in the later detailed discussion.

11.1.1 Theoretical Analysis

From the theoretical point of view we are interested primarily in attacks against submerged submarines, though an antisubmarine action often involves gunfire or ramming when the submarine is surfaced. The submarine may have been detected on the surface initially, or it may have been forced to the surface by previous attacks. In either case the ensuing action on the surface is little different from any other surface action and needs no consideration here.

When the presence of a submerged submarine has been detected by sonar, the initial step in the attack is to "localize" the submarine, i.e., to determine its range and bearing from the attacking ship. On the basis of continuing range and bearing data, the submarine must then be "tracked" in order to determine its course and speed. Sometimes this is done explicitly by plotting positions, but more often it is done implicitly.[a] Finally, the attacking ship must maneuver into a position such that when it launches its explosives they will reach a point beneath the surface at the same time as the submarine reaches that point. Figure 1 illustrates a typical attack in which the barrage is laid off the stern and to the quarters of the attacking ship, and Figure 2 illustrates an attack in

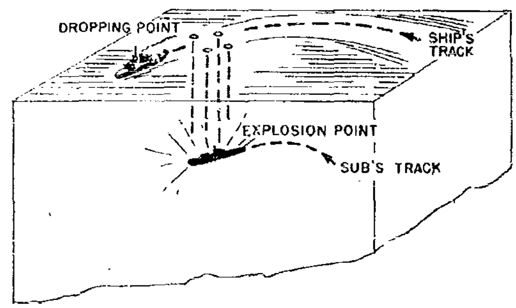


Figure 1. Stern dropped attack.

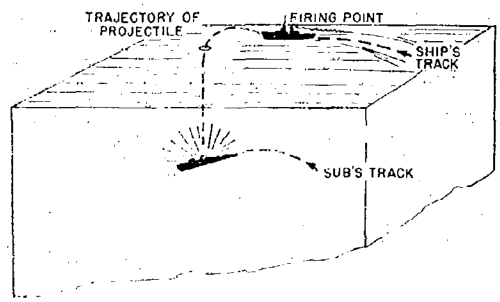


Figure 2. Ahead thrown attack.

[a] Standard doctrine presented in FTP 223A for the use of cut on technique and range recorder is an example of an implicit tracking procedure. Range rates, recorder traces, and changes in bearing are used to give rules for carrying out the attack. The antisubmarine attack plotter, on the other hand, is a device for explicit tracking, since it presents a geographic plot of submarine motion.

which the explosives are thrown ahead of the attacking ship. These explosives may be activated by contact fuzes as in the case of Mousetrap or Hedgehog projectiles; by proximity fuzes, as in the case of Mk 8 and Mk 14 depth charges; or by depth fuzes, as in the case of conventional depth charges or "Squid." If the attacks illustrated in Figures 1 and 2 are to be successful, the charges must explode sufficiently close to the submarine either to rupture its pressure hull and cause immediate sinking or to damage the hull sufficiently to force it to the surface where it can be sunk by gunfire or ramming.

11.1.2 Operational Studies

Theoretical investigations usually involve a detailed analysis of the attack problem, but this is not possible in the case of studies based on operational data because of the nature of the information available. The primary source of data for operational analysis is the action report prepared by each vessel which has made an attack. All attacks made on the same submarine during a more or less continuous engagement are grouped as one incident, whose results are assessed by the appropriate committee. The assessments are graded A to J as follows.

- A. Known sunk.
- B. Probably sunk.
- C. Probably damaged, possibly sunk.
- D. Probably damaged.
- E. Probably slightly damaged.
- F. Insufficient evidence of damage.
- G. No damage.
- H. Presence of submarine uncertain.
- I. Target attacked not a submarine.
- J. Insufficient evidence to assess.

Assessments of this type have a number of limitations as a measure of the success of the attack. In the first place, there is often some uncertainty as to whether the target attacked really was a submarine. If the submarine is not seen at any time, it is difficult to resolve this uncertainty on the basis of sonar data, and many attacks must consequently be assessed H. The usual solution is to eliminate from any analysis all attacks assessed H, I, or J. This is by no means a perfect solution, however, for a submarine is probably present in a considerable number of H attacks. Assessment of damage is also somewhat uncertain since debris and other visible evidence may not in any particular case give a very accurate indication of the actual damage inflicted on the submarine. For purposes of analysis the assessments are usually grouped in the following categories.

Sunk	A, B
Damaged	C, D, E
Undamaged	F, G
Nonsubmarine	H, I, J

As shown in Appendix I, the total number of A and B assessments did actually correspond closely to the total enemy submarine losses during World War II.

The other data concerning the attack are often less reliable than the assessment. The submarine's behavior is completely unknown, as a rule, and data from the attacking ship are likely to be undependable. Ranges, bearings, and times are recorded in the heat of battle or later from memory, and in either case are likely to be inaccurate (if they are, in fact, recorded at all). For this reason the recorded data cannot be used as a basis for a reconstruction of the attack with any high hopes of accuracy. Even in practice attacks, where the data are taken more carefully and submarine maneuvers are known, it is almost impossible to determine within a reasonable margin for error how close the barrage came to the submarine without some special device for doing so. The detailed course of events during an attack on any enemy submarine can rarely be determined, so that operational analysis consists of evaluating statistically the effect of different changes in conditions or methods of attack on the overall success as embodied in the incident assessment. Results of such operational studies can then be compared with those of theoretical investigations based on a detailed consideration of the factors influencing probability of success. In order to do this the importance of some of these factors must first be indicated.

11.2 THEORETICAL DISCUSSION OF FACTORS DETERMINING THE SUCCESS OF ATTACKS

The factors determining the probability of success in an attack can be grouped in two general categories: attack errors on the one hand and weapon lethality on the other. The first problem encountered in examining the attack errors in detail is the estimation of errors involved in localization. Ranges and bearings on the submarine are obtained by sonar,

which is subject to certain disturbances and limitations. In the first place, echoes are obtained not only from the submarine but from its wake, from water disturbances caused by previously exploded charges, from the wakes of surface vessels, from the ocean floor (in shallow water), and occasionally from the surface of the water. A good sonar operator is not easily led into thinking that these spurious echoes originate from the submarine itself, but it is inevitable that a certain amount of error and confusion creeps into range and bearing information. In addition, an inexperienced sonar operator may easily mistake a false target for the submarine and hence bring about an attack which is wholly futile. An indication of the importance of such mistakes is given by Table 1 which shows the frequency of errors in practice ahead-thrown attacks made at sea on "tame" submarines. It will be noted that the percentage of attacks on false targets is considerable even when an actual submarine is known to be in the immediate vicinity.

TABLE 1. Attacks on false contacts in practice attacks.

Area	Type attacks	Number on submarine	Number not on submarine	Percentage not on submarine
Bermuda	Hedgehog	64	18	22
Guantanamo	Mousetrap	59	10	14
Key West	Hedgehog	170	40	19
Key West	Mousetrap	575	259	31
New London	Mousetrap	32	8	20
San Diego	Hedgehog	86	13	13
San Diego	Mousetrap	162	22	12
Total		1148	370	24

Even assuming the contact to be on the submarine (or on some wake disturbance near and moving with the submarine), errors in sonar data are by no means negligible. Figure 3 shows how errors in range and bearing may be introduced by the submarine's wake, as an example. It has been estimated that the average overall bearing errors are about 2 degrees if BDI (bearing deviation indicator involving lobe comparison for accurate bearings) is used and 4 degrees and 5 degrees if cut-on bearing procedures are used. The probable range error under the same conditions has been taken as 11 yd. These estimates include a normal amount of wake echo and other errors usual in sonar operation. These errors are, of course, dependent on sonar conditions and sea state. When sound

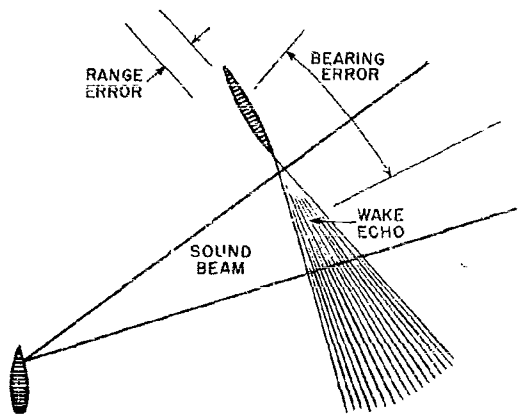


FIGURE 3. Errors introduced by wake echo.

conditions are bad, the sonar operator is somewhat more likely to make errors. Roll and pitch of the ship in high seas introduce errors for several reasons. Present sound gear is not stabilized, so that violent roll and pitch introduce errors in the bearing recorded and also make it difficult for the operator to keep the projector trained on the target. In addition, operator efficiency is reduced when the operator is training the gear with one hand, holding on to the bulkhead with the other, and combatting seasickness at the same time. The importance of such factors can hardly be determined theoretically, but operational data on the overall effect of these variables will be presented in a later section.

One of the most serious limitations on sonar information is the minimum range at which it can be obtained. Figure 4 illustrates the reasons for this minimum range with present United States sonar. Because of the limited depression angle of the sound beam, the submarine can pass under it. This causes the ship to conduct the final part of a stern-dropped attack after contact with the target has been lost. Table 2 gives the average range of lost contact in attacks by United States surface craft. The increase of

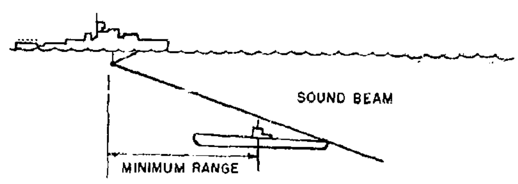


FIGURE 4. Minimum range on a deep submarine.

TABLE 2. Lost contact ranges.

Period	Average range at which sonar contact was lost
July 1942–Dec 1942	176 yd
Jan 1943–July 1943	192 yd
Aug 1943–Feb 1944	223 yd
Mar 1944–May 1945	279 yd

average range reflects the increase in average depth of submergence of U-boats when attacked.

The maximum sonar range is also of importance, primarily in regaining contact for repeated attacks. If the maximum range is less than about a thousand yards, the attack is made difficult because the attacking ship cannot maneuver freely and remain in contact with the submarine. For greater ranges, however, maximum range has little effect on the accuracy of attack.

Sonar ranges and bearings, such as they are, must be used in endeavoring to place the explosives so that they will arrive at a point beneath the surface at the same time the center of the submarine arrives at that point. How is this placement to be made, and how much in error will it be?

The most important factor in this problem is the "blind time," defined as the time elapsed between reception of the last useful information concerning the submarine's position and the arrival of the explosives at the predetermined depth. In the case of ahead thrown attacks the barrage is usually fired before contact is lost, making the blind time simply the time of flight of the charges plus the time required for them to sink to the proper depth. For a stern-dropped attack the blind time is usually about a minute or more; for an ahead thrown attack it may be as little as 15 sec. Since these are long enough for the submarine to move a considerable distance, it is necessary for the conning officer on the antisubmarine ship to estimate this movement and allow for it in placing his barrage. Figure 5 shows the tracks of ship and submarine in a typical depth-charge attack, and indicates the necessity for taking the blind time into consideration. In this case 50 seconds elapse between loss of contact and explosion of the depth charges. It is necessary for the conning officer to track the target from time 0 sec to time 40 sec, determine its course and speed, either implicitly or explicitly, and then, on the basis of this information, determine where it will be at time 90 sec.

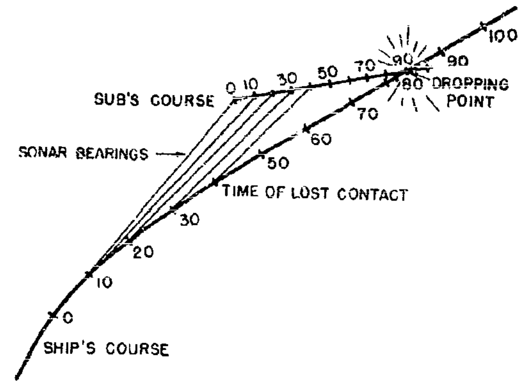


FIGURE 5. Plot of typical attack (figures give time in seconds).

In carrying out an attack the conning officer does not know the submarine's motion beforehand but must infer it from sonar range and bearing data. Normally this tracking is done implicitly as ranges are plotted on the sound range recorder in such a way as to allow rapid determination of the rate of change of range. From this information the recorder computes the time to fire the barrage. To determine the course which should be steered in order to place the charges at the proper point, the conning officer ordinarily observes the rate of change of bearing and applies lead angle according to simple rules. Frequently, however, the attack is carried out by watching the plot of the attack furnished by the antisubmarine attack plotter. In this case a plot quite similar to that of Figure 5 is presented. The conning officer estimates the geographical position of the submarine at explosion time (90 sec in Figure 5) and steers his ship accordingly. Here tracking is quite explicit.

Now, errors in placing the barrage of explosives in the attack are intimately related to blind time, method of tracking, and sonar errors. Figure 6 is a simplified illustration of this relationship. Suppose we have tracked the submarine from point A to point B, at which point we lose contact with it. Because of the sonar errors the submarine will probably lie within a distance e of point B at the time of lost contact, where e is the probable error[b] in location. Furthermore, because of these sonar errors the exact

[b] The rule of combination of errors used in equation (1) is consistent with the normal usage of the term probable error, but Figures 6 and 7 are not. They should be considered as illustrations only, not exact diagrams.

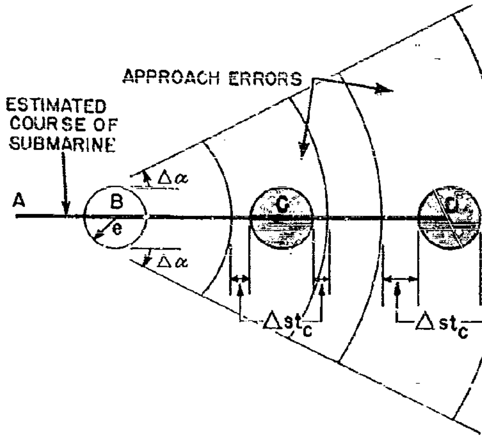


FIGURE 6. Diagram of attack errors.

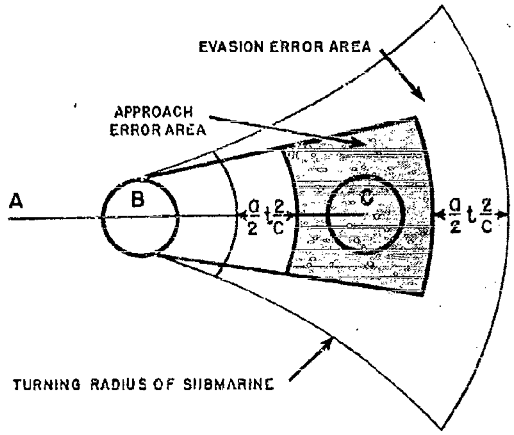


FIGURE 7. Attack and evasion errors.

course and speed of the submarine at point B are not known. Suppose that the probable error in course estimation is $\Delta\alpha$ and the probable error in speed estimation is Δs. Now suppose that we estimate C to be the point at which the submarine and the barrage will arrive simultaneously, that is, the point of explosion of the charges. Then the blind time t_c is the time required for the submarine to travel at its estimated speed from B to C. Because of the errors involved, the submarine is not likely to be at point C at the time the charges arrive there, but probably will be somewhere within the shaded area around C. The probable error in the attack (the typical distance between the center of the barrage and the center of the submarine at the time of explosion) will be approximately proportional to the square root of the area. If the blind time were longer so that D was the estimated point of explosion, the shaded area would be larger, and hence the probable error of the attack would be larger. It is apparent from Figure 6 that the area within which the submarine lies is approximately proportional to the square of the blind time and, therefore, that the probable error in the attack is approximately proportional to the blind time.

In Figure 6, however, we have assumed that during the blind time the submarine maintains the same course and speed it had at point B where contact was lost. In this case the error in the attack is called the approach error. Unfortunately, submarines can and do change their course and speed very considerably, giving rise to an evasion error as well. Figure 7 is, therefore, a more realistic picture of the area within which the submarine may lie after a blind time t_c. This area, it will be noted, is made up of two parts, one of which is the approach area of Figure 6, the other an evasion area dependent on the turning circle of the submarine, its acceleration a and the blind time t_c. This second area measures the submarine's evasive capabilities and increases in size approximately as the cube of the blind time. The total shaded area in Figure 7 represents the total plan error in placing the barrage. If the three sources of error are assumed to be independent, the effective area in which the submarine may lie is written as in equation (1).

$$A = k_1^2 + k_2^2(vt)^2 + k_3^2(at)^3, \qquad (1)$$

on the assumption that errors in estimating submarine velocity are proportional to the velocity. A more complicated assumption would replace the v^2 term with other powers of v, not greatly altering the dependence of A on v. The k's are constant, v is the submarine speed, and t is the blind time. To calculate the values of the k's from physical characteristics of the gear which is used is an involved process, and therefore we will merely consider them as empirical constants.

Analysis of experimental data derived from practice attacks at sea and on the attack teacher has shown that the distribution of attack errors is in most cases similar to a Gaussian distribution. For purposes of calculation, therefore, it is frequently assumed that the attack error distribution is, in fact, Gaussian.

TABLE 3. Errors in practice attacks.

Example number	Type of attack	Reported by	Method of attack	Submarine course	Submarine speed (knots)	Average range of lost contact (yards)	Sinking time (seconds)	Average attack error (yards)
1	Stern dropped	ASDevLant	Attack teacher	Straight	0	200	25	55
2	Stern-dropped	ASDevLant	Attack teacher	Straight	3	200	25	91
3	Stern-dropped	ASDevLant	Attack teacher	Straight	5	200	25	99
4	Stern-dropped	ASDevLant	Attack teacher	Straight	7	200	25	124
5	Stern-dropped	ASDevLant	Attack teacher	Highly evasive	5	200	25	117
6	Stern dropped	ASDevLant	Attack teacher	Evasive	7	200	25	152
7	Stern dropped	ASDevLant	At sea	Evasive	About 3	Less than 100	25	55
8	Stern dropped	COTCLant	At sea	Highly evasive	About 5	Over 100	20	170
9	Ahead-thrown (Hedgehog)	CTF	At sea	Evasive	About 3	Not lost	12*	41

* Includes time of flight.

Equation (1) indicates that the corresponding probable error would be given by

$$E^2 = K_1^2 + K_2^2(vt)^2 + K_3^2(vt)^3 \qquad (2)$$

where E = radial probable error of attack,
v = submarine speed,
t = blind time,
K_1, K_2, K_3 = empirical constants.

Equation (2) must be considered as an approximate expression in which the coefficients vary widely according to the evasive capabilities of the submarine and the tracking capabilites of the antisubmarine ship. The important point is merely that the attack error increases rapidly with increasing blind time, so that the chief problem in improving the effectiveness of antisubmarine attack is that of reducing the blind time.

The probable error E described above is a horizontal or plan error only. A vertical or depth error is also present in most attacks because of uncertainty as to the depth of the submarine. Very few United States ships have been fitted with depth-determining sonar, and consequently errors in estimation of depth have been large. A rough estimate is given by the range at which contact is lost, but it is not at all reliable. Means of reducing the depth error are, therefore, of very great importance.

Having considered the various sources of attack error, we must now determine what the overall magnitude of the error E is under some typical conditions. It is not possible to determine attack errors from operational data, since we do not have sufficiently detailed data concerning attacks on enemy submarines. There is, however, a fairly considerable amount of data available from practice attacks where records are sufficiently complete. Two sources are available. One consists of the runs made on the attack teacher, which is a mechanical device for reproducing the conditions of an attack at sea; the other, of practice attacks made at sea against friendly submarines. Table 3 presents representative data from both sources. In all these attacks the depth of the submarine was known, so that only plan errors are involved.

The first conclusion which can be drawn from Table 3 is that the attack errors increase with increasing submarine speed, other things being equal. This is shown by comparison of examples 1, 2, 3, and 4. There are a number of reasons for this increase. The distance traveled by the submarine in the blind time is increased by higher speed, so that the shaded areas shown in Figures 6 and 7 are larger for higher speeds. In addition the average blind time is increased because the majority of attacks end with the submarine heading away from the ship, in which case high submarine speed results in a low rate of closing the range. Finally, attack on a high-speed submarine may require somewhat more difficult maneuvering by the attacking ship.

Examples 5 and 6 show somewhat greater errors than do examples 3 and 4 because of the submarine's evasive maneuvers, but the difference is not so large as might be expected. In these attacks however, the nonevasive attacks were mixed with the evasive ones so that the conning officer did not know ahead of time whether the submarine would evade or not. In

such a case erroneous indications of evasive maneuvers are frequently acted upon and the charges dropped in the evasion area of Figure 7 rather than in the approach area. Thus an evasive error exists, in effect, whether the target actually evades or not, as long as it has evasive capabilities which the attacker thinks it might use. The errors given in examples 1 to 6 can, however, be well represented by an equation of the same type as (2), namely,

$$E = \sqrt{60^2 + 240s^2 + 22s^3}. \tag{3}$$

This is done in Figure 8, and it is observed that the agreement is good.

Examples 7 and 8 show the large effect of training on the accuracy of attack. The short lost contact ranges and low speed involved in example 7 would lead one to predict an error of about 75 yd on the basis of the curves in Figure 8. The small observed error, 55 yd, probably indicates exceptionally high skill on the part of this ASDevLant team. In the case of example 8, the expected error would be about 115 yd for a 5-knot submarine, but the actual probable error was 170 yd. This effect might be expected, since crews in the training at COTCLant were probably a good deal less skillful than the ASDevLant teams, because of less training and experience.

Of particular importance is the figure for ahead thrown attacks in example 9. The error given, 11 yd,

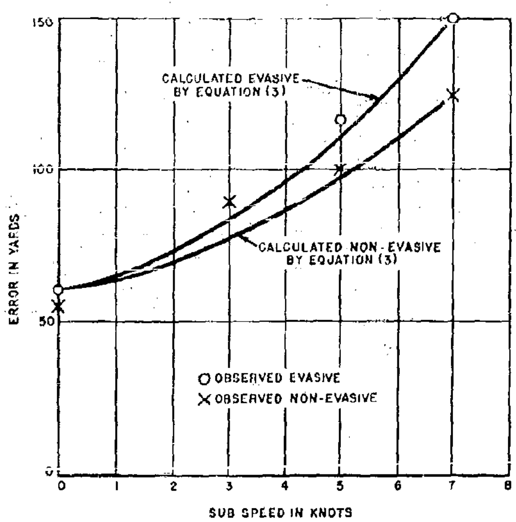


Figure 8. Probable attack errors (Table 3, examples 1 to 6).

is less than that for stern-dropped attacks on a stationary submarine in example 1. It is reasonable to conclude that the errors involved are those of locating the submarine—the term K_1—and that the blind time for these ahead-thrown attacks is short enough largely to eliminate submarine evasion error and prediction error (the K_3 and K_2 terms).

So much for the attack errors. We are not interested in them for their own sake, but only for their effect on the probability of success in an attack. The next step is to determine the probability of a barrage launched in an attack proving lethal to the submarine. In order to calculate this probability of lethality or "effectiveness," both the attack errors and the characteristics of the barrage itself must be taken into account.

11.2.1 Weapon Lethality

The method of taking the characteristics of the barrage into account can best be made clear by an example. Suppose we are dealing with a depth-charge barrage such as the one shown in Figure 9. If a depth charge explodes immediately alongside of the submarine, it will undoubtedly make a large hole in the pressure hull and almost surely sink it. If the depth charge is many miles away, it will cause no damage. The transition between these two situations is probably a gradual one with a considerable region in which an exploding depth charge may sometimes cause the submarine either to sink or to surface and may sometimes fail to do so, depending on the strength of the particular submarine and on the morale and skill of its crew.

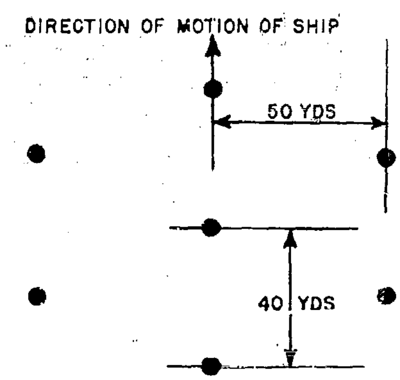


Figure 9. Seven-charge depth-charge pattern (hypothetical).

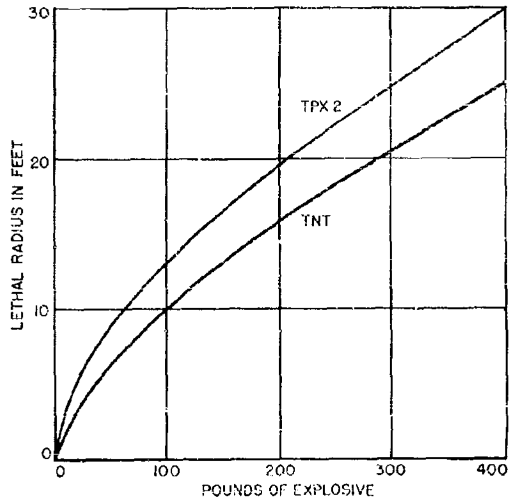


FIGURE 10. Comparison of lethal radii of Torpex 2 and TNT ($\frac{7}{8}$-in. HTS hull).

Experimental evidence suggests that the pressure hull will be split if the charge explodes within a certain lethal radius of it. The lethal radius depends on the weight and type of explosive and on hull thickness, but its exact determination is difficult. The ideal method of determination would involve actual tests against enemy submarines, but this is rarely possible and most tests are made on models. In Figure 10 curves showing the lethal radius for TNT and Torpex as a function of charge weight are given for a $\frac{7}{8}$ in. HTS hull.

Although these curves cannot be taken as giving exact lethal ranges, it is believed that they give a good indication of effectiveness against the types of submarines encountered in World War II. In order to simplify calculations it is usually assumed that all charges exploding within a fixed lethal (or surfacing) radius cause lethal (or surfacing) damage and that no others are effective. For any given position of an exploding depth charge there is, then, a "commanded volume" which has the property that any submarine whose center lies in the commanded volume is sunk, but any other submarine is unaffected.

11.2.2 Calculation of Barrage Lethality

The actual method of using the commanded volume to calculate the effectiveness of a barrage follows. First, a three-dimensional outline of the pressure hull is drawn around each charge, centered at the charge's explosion point and oriented at the appropriate target angle (for example, 150 degrees). An envelope is drawn around these outlines so that it is everywhere 21 ft from them (for lethal radius of 21 ft). The results of this construction are shown in Figure 11. Now if the center of the submarine lies within these commanded volumes of Figure 11, it will be sunk. Therefore to determine the lethal probability of the barrage it is only necessary to determine the probability that the center of the submarine will lie within the commanded volume. This probability is determined by the distribution of attack errors, denoted by $p(x, y, z)$, defined so that $p(x, y, z)dxdydz$ is the probability that the center of the submarine will be in position (x, y, z) relative to the center of the barrage at the time the charges explode. The probability P that the center of the submarine will lie in the command volume is

$$P = \iiint_{\text{Commanded volume}} p(x, y, z)\, dx\, dy\, dz. \tag{1}$$

The integration indicated in equation (1) is ordinarily carried out by graphical methods, working first with the plan errors, then with errors in depth. Since the commanded volume varies with orientation of the submarine, the process must be carried out for a number of target angles in order to obtain an average effectiveness for the barrage. The overall conclusion, however, is obvious. P increases with increase in the commanded volume and decreases as the attack errors increase.

The commanded volume depends, of course, on the type of ordnance employed. Suppose that a barrage of contact-fuzed charges, rather than depth charges, had

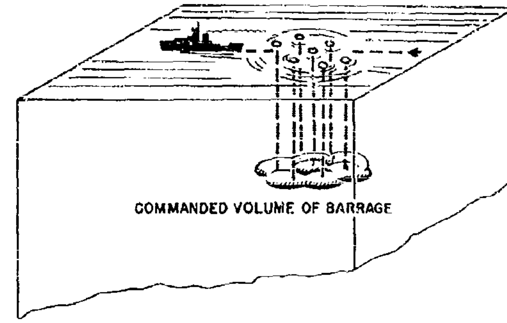


FIGURE 11. Commanded volume for hypothetical barrage.

been considered in the above discussion. The commanded volumes of Figure 11 would then consist of cylinders having a cross section approximately equal to that of the submarine[e] and extending from the arming depth down to the floor of the ocean. In this case the commanded volume would be much larger than for depth charges. If depth errors are large, that is, if $p(x, y, z)$ has an appreciable value over some two or three hundred ft in depth, this additional volume would result in a larger value of P a more effective barrage for the contact charges. If, on the other hand, the depth errors were limited to 30 ft or so, the greater concentration of the depth-charge commanded volume within this region due to greater lethal radius will cause the value of P to be larger for the depth-charge case than for the contact-charge barrage. In general, depth errors are very large with present United States equipment so that the additional commanded volume of contact charges has been a point very much in their favor. Like contact charges, proximity charges cover a wide range of depth. Their commanded volumes are cylinders of cross section approximately equal to that of a depth charge. This being so, the amount of commanded volume of proximity charges lying within the desired depth range is always as great as, or greater than, that of depth charges. Charges equipped with proximity fuzes are, therefore, as effective as similar charges equipped with depth pistols when depth errors are small and many times more effective when depth errors are large.

[e] A slight correction must be made to take account of charges that either hit glancing blows on the sides of the submarine and fail to explode or hit and explode in some position too far from the pressure hull to be lethal.

Figures for the effectiveness of various types of barrages are presented in Table 4. The theoretical advantage of ahead-thrown weapons due to decreased blind time (and greater commanded volume for Hedgehog and Mousetrap) is clearly shown. At first thought one might expect the Squid to be much less effective than Hedgehog because it employs depth charges rather than contact-fuzed charges, thereby commanding a much smaller volume. Squid is used, however, in conjunction with depth-determining gear which lowers the probable depth error to a point where the large lethal radius of the Squid largely makes up for the Hedgehog's ability to cover a large range of depths. In addition, the higher sinking speed of the Squid projectile gives a somewhat shorter blind time. For very deep submarines this becomes important and Squid is considerably the more effective weapon. It has the extra advantage that nonlethal barrages may still bring the submarine to the surface where it can be sunk by other weapons.

11.2.3 Calculation of Probability of Success per Incident

Up to this point only single attacks have been discussed. Usually, however, an action against a submarine consists of a number of attacks which are grouped together as an incident for purposes of assessment. Unfortunately for the antisubmarine team, it cannot always deliver as many attacks as it may wish. In the first place, contact is usually lost for the reason illustrated in Figure 4. Contact may also be lost during an attack as a result of water disturbances of one kind or another. In the second place, there

TABLE 4. Theoretical effectiveness of antisubmarine barrages.

Weapon type	Submarine depth assumption	Fuze	No. of charges	Lethal radius (feet)	Probable effectiveness (per cent)
Side-stern launched depth charges	Equally likely from 100–300 ft depth	Depth pistol	9	21	6
Side-stern launched proximity charges	Equally likely from 100–300 ft depth	Influence pistol	9	21	24
Hedgehog (Mk 10)	Equally likely from 100–300 ft depth	Contact	24	Contact	28
Mousetrap (Mk 22)	Equally likely from 100–300 ft depth	Contact	16	Contact	17
Squid	At 200 ft depth with 30 ft standard error on account of depth determining feature	Depth pistol	3 or 6	21	16 or 26

is never a 100-per cent probability of regaining contact once it has been lost. The formation of wakes, knuckles, and explosion disturbances often causes contact to be lost permanently after a small number of attacks. A well-trained team working in good sonar conditions will not experience great difficulty in regaining contact, but a poor team working under poor conditions will find it almost impossible to do so. The theoretical probability of success in an incident is thus a function both of the probability of success in a single attack and of the probability of regaining contact after the attack. On the assumption that the probability of regaining contact after an attack is a constant, independent of the number of attacks previously made, the following equation can be written.

$$P_t = P_a + C(1 - P_a)P_a + C^2(1 - P_a)^2 P_a + \cdots + C^n(1 - P_a)^n P_a$$

$$= P_a \frac{1 - C^n(1 - P_a)^n}{1 - C(1 - P_a)}, \qquad (5)$$

where P_t = probability of success per incident,
P_a = probability of success per attack,
C = probability of regaining contact,
n = total number of attacks which can be delivered without exhausting ordnance.

Operational data indicate values of C varying from 0.50 to 0.90, depending on the number of ships present, period considered, and other factors. Table 5 presents some typical values.

TABLE 5. Probability of regaining contact.

	Single ship	Coordinated group of ships
Jan 1943–July 1943	0.54	About 0.8
Aug 1943–Feb 1944	0.68	About 0.9

Since the probability of success per incident is much improved by an increase in probability of regaining contact, this is a strong argument for the use of coordinated groups of ships.[d]

[d] The interpretation of these figures is open to some question, however, because incidents have normally been classed as coordinated only when several ships actually attacked the submarine. Cases in which several ships were on hand but only one released depth charges are not usually counted as coordinated. This type of selection introduces a bias such that coordinated incidents may be credited with values of C (and of lethality) which are higher than those actually obtained in operations.

Although this discussion has presented by no means all details of attack theory, the main ideas have been mentioned. Accordingly, it is now desirable to consider operational data which can be compared with the theoretical predictions.

11.3 OPERATIONAL DATA ON EFFECTIVENESS OF ATTACKS

The data available concerning attacks on enemy submarines are not sufficiently complete to enable one to reconstruct the details of each attack. For each incident (which may involve several attacks) certain basic information can be obtained as to the conditions under which attacks were made, the weapons used, the ships involved, and the resulting success as expressed in the assessment of the attack.[e] Most analyses of operational data therefore consist of breakdowns to determine the effect of changes in the conditions or nature of attack on the success as evidenced by the assessment. Some figures of this type will now be presented which are typical of the results obtained from operational data.

11.3.1 Factors Influencing Attack Errors

As was pointed out in the previous section, two overall factors determine the probability of success in an antisubmarine attack: the attack errors and the weapon effectiveness. One of the variables which is of importance in determining accuracy is the state of the ocean with respect to sound transmission. If sound conditions are bad, the overall effectiveness of the ships will be reduced. Data are presented in Table 6 which show that such is indeed the case.[f] These figures, it should be noted, are given on a "per incident" basis. The effectiveness of an incident depends both on the probability of success in a single barrage and on the number of barrages that can be dropped in an incident before contact is lost.

[e] During the course of World War II, this assessment was based on visible evidence of damage, survivors from the U-boat, if any, and supporting intelligence. After the German surrender, however, captured documents have become available to supplement this information, and assessments have been revised. The data presented here are based on the earlier wartime assessments. See the Appendix and Chapter 8 for further discussion of this question.

[f] The figures given are for United States attacks from July 1942 to July 1943 assessed A to G, for which the information necessary to estimate sound conditions from oceanographic considerations was given.

TABLE 6. Effect of sonar conditions on attack effectiveness.

Sound conditions	Number of incidents: Assessed A–G	Number of incidents: Assessed A–E	Percentage of damaging incidents
Good–Fair	120	27	22
Poor–Bad	74	5	7

Through the combination of these effects, good sound conditions lead to a larger fraction of submarines damaged or sunk per submarine encountered.

Another source of error and difficulty in localizing the submarine with sonar is the roll and pitch of the ship. Present sound projectors are not stabilized, so that if the ship rolls and pitches violently, the operator has difficulty in keeping the projector pointed at the target. Much information is lost in this manner, and, furthermore, rather serious errors may be noted in the bearings if they are taken at one or the other extreme of the ship's roll. In addition, general operator efficiency is reduced under such conditions. The figures given in Table 7 show that such an effect apparently becomes important in seas classed as rough or higher. (The numbers are too small to give definite proof.) Moderate seas show no deleterious effect, however, possibly because smooth seas are likely to be accompanied by thermal gradients and layering which cause poor sound transmission.

TABLE 7. Effect of sea state on attack effectiveness (U. S. attacks from July 1942–July 1943).

State of sea	Number of incidents: Assessed A–G	Number of incidents: Assessed A–E	Percentage of damaging incidents
Calm, smooth, slight	116	20	17
Moderate	50	10	20
Rough and higher	13	1	8

The attack errors depend on many things besides oceanographic conditions. The type of ship and sound gear involved in the attack have a great deal to do with it, as do the experience and skill of the attackers, the depth, speed, and evasive maneuvers of the submarine. Concerning the last we have no information since we do not know what the enemy submarine really did in any of the attacks. The type of sound gear involved is undoubtedly of importance, but United States experience involved only one general type of sonar gear. Even variations such as use of BDI would not be expected to result in a major increase in effectiveness such as would be clearly evident in operational data. A considerable number of Japanese attacks were, however, made using listening gear only. Comparison of their effectiveness as estimated from United States submarine experience with that of echo-ranging attacks is made in Table 8. The difference between attacks of the two types is very striking and must be largely due to the superior accuracy of echo-ranging gear. The difference between United States and Japanese echo-ranging attacks is probably largely due to differences in skill of personnel involved, though United States gear was undoubtedly the better of the two.

TABLE 8. Effectiveness of listening and echo-ranging attacks.

	No serious damage (per cent)	Major damage (per cent)	Submarines sunk (per cent)
Jap attacks on U. S. subs (July 1, 1943–March 31, 1944)			
Listening	99	1	0
Echo-ranging	87	12	1
U. S. attacks on U-boats using echo ranging			
1943	85	10	5
1944	65	5	30

The effect of training and experience on the part of the attack team is one which was of extreme practical importance in the Battle of the Atlantic. Perhaps the best example of improvement with experience is a set of figures on the success of Hedgehog attacks compiled by the British. The data are given in Figure 12. The rise from an effectiveness of 7.5 per cent per attack in 1943 to over 20 per cent in late 1944 and 1945 must be ascribed largely to training, since there was no radical change in the type of sound gear used, nor in the enemy's evasive tactics. The values in Figure 12 are given on a per attack basis,[g] unlike those in Tables 6 and 7, which are on a per incident basis. Consequently, any changes in the number of attacks made per incident should not affect these values. The individual attacks made were undoubtedly more accurate in the recent periods than they

[g] In the analysis, attacks thought to have been made on the U-boat's wake or made after a kill had already been assured are not counted. Hence the figures are a fairly pure measure of weapon effectiveness.

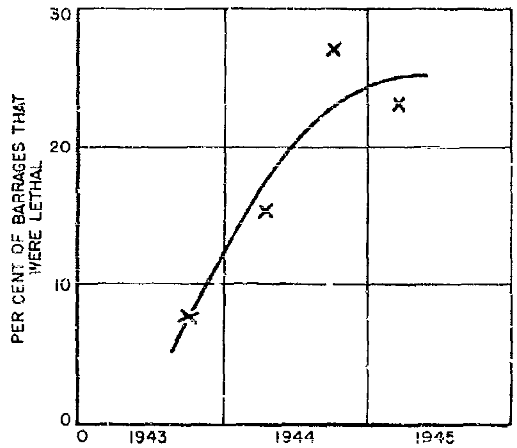


FIGURE 12. Success of British Hedgehog attacks.

were when the weapon was new and crews inexperienced in its use.

It is evident that the points plotted in Figure 12 indicate a marked rise in effectiveness to a value of about 20-30 per cent, in accordance with the theoretical figures in Table 4. In the first months of Hedgehog use, its results were very disappointing, since earliest theoretical predictions were more optimistic than 25 per cent. After the weapon had been in use for a year or so, however, it was used much more effectively, and theoretical studies were made somewhat more conservative as a result of a better understanding of the problems involved, so that the theoretical predictions and the results now agree.

The effect of experience and training can also be illustrated by the results obtained by United States crews in depth charge attacks during the early years of the war. Figure 13 shows two curves—an effectiveness per charge and an effectiveness per incident. The increase in probability of success per incident is obviously greater than the increase per depth charge dropped. The latter measures the increase in attack accuracy, whereas the overall figure also depends on the number of charges dropped per incident. In Figure 13B the theoretical effectiveness per depth charge is given for comparison with results achieved. In the early period there was a considerable discrepancy, but the agreement became fairly good in later periods. The even more abrupt rise in Figure 13A indicates that larger barrages, greater skill in regaining contact, and more frequent coordinated attacks contributed a great deal to increase the overall effectiveness of incidents.

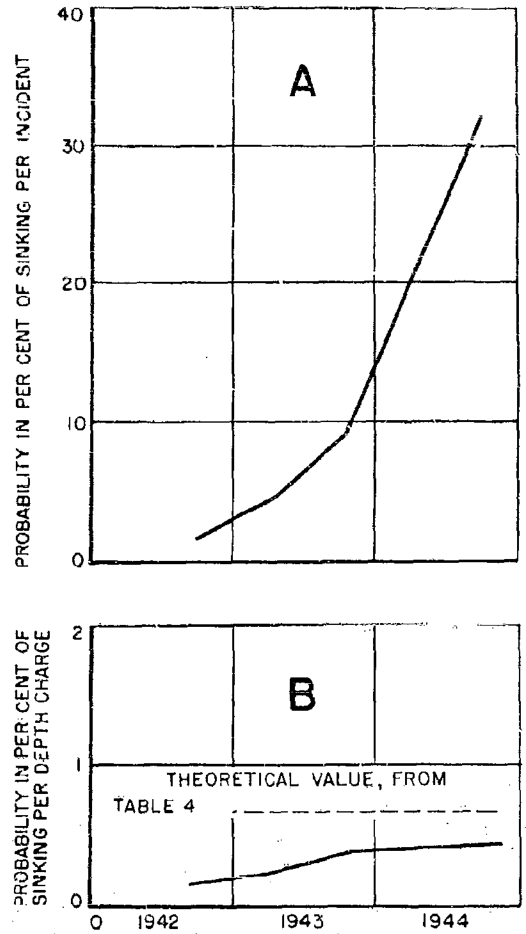


FIGURE 13. Success of U. S. depth charge attacks.

11.3.2 Comparative Effectiveness of Weapons

So much for the influence of factors having to do with attack accuracy. The weapon used is also of importance, and operational data can be used to show the relative merits of different types of ordnance. The most widespread innovation in the course of World War II was the introduction of Hedgehog. A comparison between Figures 12 and 13 suggests that operational data do bear out the theoretical value of the Hedgehog attack. A direct comparison is presented in Table 9. There is a training factor which must be kept in mind. During the early periods Hedgehog was not used in such a way as to realize its full effectiveness.

TABLE 9. Comparison of Hedgehog, depth charge, and Squid. (On a per barrage basis.*)

Period	Nationality	Depth charge	Hedgehog	Squid
1st half 1943	British	5.4%	......	......
2nd half 1943	British	4.0%	7.5%	......
1st half 1944	British	6.1%	15.4%	......
2nd half 1944	British	5.1%	28.1%	18.2% (single) 33.3% (double)
1st quarter 1945	British	7%	23%	62%
Aug 1942–June 1944	All Allied†	4.0%	8.0%	......
Mar 1944–May 1945	U. S.	4.5%	9.9%	......

* As mentioned in Section 11.3.1, British studies discard attacks not thought to be potentially effective and therefore give higher figures than those based on all attacks including some on wakes, bubbles, etc.
† Based on only those incidents in which Hedgehog was used for at least one attack.

In evaluating the depth charge versus Hedgehog comparison, it must be kept in mind that Hedgehog attacks may, on the whole, have been made by better-trained ships, in better sound conditions, or on shallower submarines, since Hedgehog is not to be used under unfavorable conditions. In the figures quoted for August 1942 to June 1944, however, only depth-charge attacks made in incidents which involved Hedgehog are counted.

In these cases the same ships are involved for both weapons and the general conditions of attack are the same. The superiority of Hedgehog is again demonstrated, so that it may be concluded that the superiority is inherent in the weapon.

The figures on Squid success are based on a very small number of attacks and cannot be considered conclusive. They are, however, even better than the theoretical predictions, as expressed in Table 1, confirming the high effectiveness expected of Squid.

As an overall conclusion on the relationship between theoretical and operational values for the effectiveness of various types of ordnance, one can say that theory gives a correct picture of the relative merits of the various types and that it also gives a reasonably accurate picture of their absolute values. In other words, theoretical studies provide a basis for evaluating the state of training of antisubmarine vessels by furnishing a standard to be reached and also indicate the direction for most profitable development of antisubmarine ordnance.

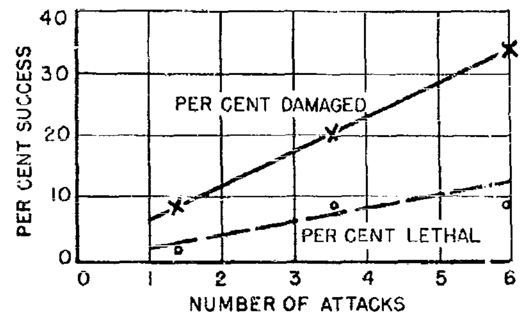


FIGURE 14. Success of incidents as a function of number of attacks (U. S. craft, January 1943–February 1944).

It has been implied throughout that the probability of success in an incident is strongly influenced by the number of attacks made: the more attacks, the greater the chances of sinking a submarine. Operational results prove that this is indeed the case. Figure 14 shows the relationship between success and number of attacks. It is evident that the percentage of damaging incidents increases steadily as the number of attacks per incident increases, corresponding to about 5 per cent damaged in each attack, which is in accordance with expectations. The percentage of lethal incidents also rises, a fact of considerable importance. It might be expected that the mere existence of a fourth attack, for example, would mean that the previous three had not been lethal, and the fraction of submarines sunk in cases where four attacks were made would simply measure the proba-

TABLE 10. Coordinated versus independent attacks.

	Independent	Coordinated
U. S. attacks, Atlantic and Mediterranean, Jan 1943–Feb 1944		
Number of incidents (A–G, + JS*)	176	18
Number assessed A or B	9	3
Per cent successful	5	17
U. S. attacks, Atlantic and Mediterranean, March 1944–May 1945		
Number of incidents (A–G, + JS*)	41	38
Number assessed A or B	5	21
Per cent successful	12	55
U. S. attacks, Pacific, December 1943–April 1944		
Number of incidents (A–G, + JS*)	184	29
Number assessed A or B	16	6
Per cent successful	9	21

* Incidents are assessed JS when a submarine is believed to have been present but complete information on the incident was not yet available at the time of study.

bility of sinking in the fourth attack. Figure 14, indicates, however, that lethal damage may accumulate as a result of a succession of attacks. When a number of attacks have been made, the next is more likely to prove lethal than it would otherwise. Figure 14 does more than confirm the importance of persistence which was demonstrated by equation (5). This equation was based on the assumption that each attack had a fixed chance of success, whereas the operational results suggest strongly that the chance gets better with each succeeding attack. It may be concluded that regaining contact for persistent and repeated attacks is of the utmost importance.

Employment of several ships in coordinated hunt does much to assure that contact will be regained a large number of times, as shown in Table 5. Correspondingly, coordinated incidents have a high probability of success. Some typical comparisons between independent and coordinated incidents are given in Table 10. The coordinated incidents are consistently at least two or three times as effective as the independent.[b]

The overall conclusions concerning antisubmarine attacks are simple. For good effectiveness three things are required: (1) good attack accuracy through proper design of sound gear and ordnance and training of personnel, (2) good weapon effectiveness through a large commanded volume, and (3) persistent and repeated attacks with good ability to hold and regain contact.

[b] This effect may be somewhat exaggerated by the method of designating coordinated incidents. If two ships make attacks a few hours apart on what was probably the same submarine, the actions involved will be likely to be considered a single coordinated incident if damage is done, two independent incidents if there is no damage.

Chapter 12

ATTACKS BY AIRCRAFT

12.1 GENERAL STATEMENT OF PROBLEM

THE GENERAL THEORY of aircraft attacks can be approached along the lines used in considering surface craft attacks. Although the details of the two subjects differ widely, many of the basic theoretical ideas developed in the previous chapter are applicable in the present one. Furthermore, the general type of operational data available and the system used in assessing attacks are the same. As before, we shall first give a brief overall description of the problem and then proceed to detailed considerations. In both cases, a priori and a posteriori aspects will be treated.

Aircraft are greatly superior to surface craft in locating submarines on the surface, but their effectiveness for underwater search and tracking is very limited.[a] As a result, aircraft are primarily of value in attacking submarines sighted on the surface. Many attacks will actually be delivered while the submarine is still fully or partly surfaced, but the rapidity with which a submarine can crash dive as the aircraft closes to attack means that attacks shortly after submergence must also be considered.[b]

When an aircraft has made contact with a surfaced submarine (either visually or by radar), it must next get into a favorable position to make an attack. Since the target is small, it is necessary to get down to a low altitude for maximum accuracy. The target will, however, usually submerge on sighting the aircraft in order to escape attack, and therefore the approach must be made in such a way as to obtain the maximum element of surprise and limit, as much as possible, the degree to which the submarine can submerge prior to attack. During the approach the course and speed of the submarine must be estimated so that allowance can be made for target motion. When the proper position has been reached, the aircraft releases its weapons. These may be either

[a] See Chapter 13 for a further discussion of this point.

[b] Use of Schnorchel by the submarine will, of course, greatly reduce the searching effectiveness of the aircraft but will not change the basic attack problem except to the extent that it increases the average degree of submergence of submarines when attacked.

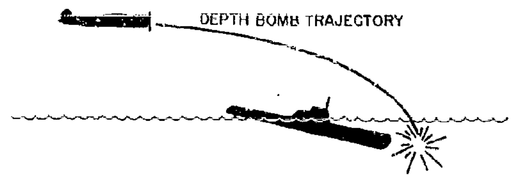


FIGURE 1. Aircraft depth-bomb attack.

rockets or bombs. As in the case of surface craft attacks, the problem is to release the weapons so that they will reach a point beneath the surface at the same time the submarine reaches that point. (See Figure 1.) From a knowledge of the characteristics of the weapons and of the position of the submarine at the time of attack, it is possible to determine where the weapons should strike the water to be effective. The probability of success will then depend on the accuracy with which the correct target position is estimated, on the errors made in placing the weapons in the desired position, and on the lethality of the weapons used.

The above factors will be considered in detail in the balance of this chapter. We shall first give a theoretical discussion and follow with a consideration of operational results. Since depth bombs have so far been the primary aircraft weapon against the submarine, operational experience is most extensive for this weapon. Certain other phases of operational results cannot be discussed at this time because highly classified information is involved. Hence much of the following detailed discussion will be confined to the depth bomb and it should be considered as an example of methods of evaluation rather than as a complete examination of the subject of aircraft attack weapons and tactics.

12.2 THEORETICAL DISCUSSION OF FACTORS DETERMINING THE SUCCESS OF ATTACKS

The factors determining the probability of success in an aircraft attack can be grouped in the same two general categories as were involved in surface craft attacks: attack errors and weapon lethality. Attack errors, in turn, may be subdivided as follows.

1. Errors in estimating submarine position.
2. Errors caused by variation in the behavior of individual missiles.
3. Aiming errors.

12.2.1 Attack Errors

If weapons are released while the submarine is still visible, errors in estimating target position will be restricted to misestimates of target motion from the time of release to the time of impact or explosion (the "blind time").[c] For rockets such movement of the submarine is so small that no allowance is ordinarily made for it. For depth bombs, the time from release to explosion will be on the order of 5 sec or so, depending on exact conditions of attack, in which time a submarine can travel only about one-half its length. It is fairly easy to make allowance for such changes in target position and errors will be negligible.

On the other hand, if the submarine submerges completely before attack, there is a longer blind time and the uncertainty of submarine position will increase with increase in this blind time, in the manner discussed in Chapter 11. The effect of a long blind time will be especially serious in aircraft attacks since there is no information as to the target's course and speed except visual estimation, and the barrage which can be dropped by aircraft is too small to cover radical changes of speed and course on submerging. The expansion of the possible area in which the submarines may be at the end of a given number of seconds after submergence is shown in Figure 2. This is based on the turning characteristics of the 500-ton German U-boat and assumes that speed may vary from 3 to 7 knots. It will be noticed that the possible area remains very small for the first 15 sec or so and then increases rapidly until, at the end of 1 minute, it is about 270,000 sq ft.

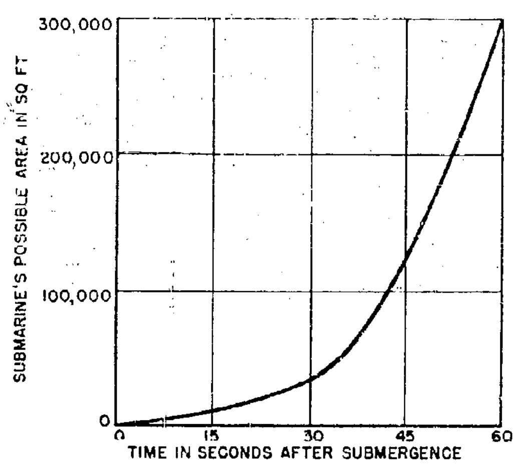


FIGURE 2. Submarine evasion area as a function of time.

From the above discussion, it is evident that attack errors due to misestimation of target position increase so rapidly with time after submergence that the probability of success quickly approaches zero. For Class A attacks, which are defined as those made on visible submarines or on submarines submerged less than 15 sec, the submarine's position is quite well known. For Class B attacks, which are attacks on submarines submerged between 15 and 30 sec, the submarine's position has become uncertain. For attacks made still later, the probable error in estimating submarine position has become extremely large. A priori, therefore, we would expect a much greater degree of success in Class A attacks than in others, the probability diminishing rapidly for Class B and later attacks. An accurate, quantitative a priori evaluation is not available, but one based on operational experience will be given later to bear out the above qualitative conclusion.

The obvious method of reducing errors of the type just discussed is to reduce blind time, that is, to make as many attacks as possible on visible submarines or, at least, on those within the Class A category. It is therefore important to employ tactics designed to achieve the greatest amount of surprise in the attack. Some of the factors involved are speed of aircraft, correct patrol altitude, approach from cloud cover, use of camouflage to avoid visual detection of aircraft, and use of countermeasures to search receivers to avoid detection of radar emissions.[d] It is also advantageous to make attacks in locations where submarines are less alert, that is, to surprise them in areas where aircraft attack is not expected. In addition to such measures, the number of favorable attacks can be increased by avoiding attacks which involve too great a blind time and which therefore have a negligible probability of success so that time and weapons may be conserved for possible future

[c] Blind time has been defined in Chapter 11.

[d] See Chapter 11.

opportunities against Class A targets. The effect of all such measures in increasing the proportion of Class A attacks is somewhat difficult to evaluate a priori, but we shall show later, from operational experience, the overall improvement which resulted from emphasis on the importance of prompt attacks involving the maximum element of surprise.

The second class of attack errors mentioned above involved those due to variation in the behavior of individual missiles. In aiming a given weapon, it is necessary to assume a certain behavior after it leaves the aircraft. Variations from this normal will, of course, occur. Depth bombs, for example, will vary in their fall through air and in their underwater travel. There will also be a variation in the depth at which they explode. Similarly, rockets will vary in flight path and in underwater trajectory. Such deviation will, of course, decrease the accuracy of the attack. Errors of this type can only be reduced by improved design of weapons. Extensive practical tests and analyses of operational results will often prove of value in determining the effectiveness of improved design.

As an illustration of the size of errors of the type just discussed, the following estimates for depth and contact bombs are quoted in Table 1.

TABLE 1. Variation of individual missiles.
(Aircraft speed 100–200 knots, altitude 50–200 ft.)

Type of bomb	Probable deviation along aircraft course (feet)	Probable deviation perpendicular to aircraft course (feet)
Round nose U. S. depth bomb	17	17
Flat nose U. S. depth bomb	7	7
Contact bomb (Hedgehog or Mousetrap)	3½	0

Considerations of target position and weapon characteristics determine the point on the water at which the weapons must strike to be effective. Errors in placing them in the desired position may be called aiming errors. This is the third subdivision of attack errors mentioned above. Aiming errors are commonly measured with relation to the aircraft's course. Errors along its course are called range errors, while those perpendicular to its course are called line errors.

Line errors are caused by failure of the pilot to fly in a straight line directly over the aim point, while range errors are due to release of bombs at the wrong moment, or, in the case of rockets, to improper altitude of the plane at the moment of firing. The size of these errors will depend on the conditions of attack, on the skill of the pilot and bombardier, and on the accuracy of the bomb or rocket sight used.

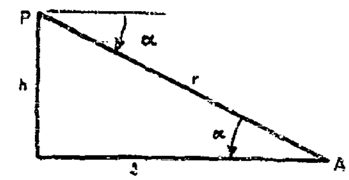


FIGURE 3. Geometry of horizontal bombing.

As an example of aiming errors and methods of reducing them, consider the problem of delivering an attack with depth bombs. The pilot flies as nearly as possible straight across the aim point and thus controls the line error. The problem as far as range is concerned is, then, to determine the proper moment for release of the bombs. For a horizontal attack, the geometry of the situation is simple. In Figure 3, P represents the position of the plane at moment of release of the center bomb of the stick, A represents aim point, h is altitude, r slant range, and l horizontal range (in feet). The angle α is the angle between the line PA and the horizontal. Then, disregarding air resistance, the center bomb will travel forward a distance $V\sqrt{2h/g}$ ft, where V is plane velocity in feet per second. Hence correct release will occur when $l = V\sqrt{2h/g}$ or $r = \sqrt{h^2 + V^2 2h/g}$ or when α has the value determined by the relationship $\tan \alpha = h/l$. Hence the aiming problem in range can be solved for a given altitude by selecting either the proper slant range, horizontal range, or angle between the horizontal and line from aircraft to aim point. Use of r is indicated for radar bombsights since slant range can be determined by radar. Use of the angle α is involved in using the reflector gunsight which enables determination of this angle. In addition to the above means it is possible to utilize the rate at which the angle α is changing, as is done in the angular velocity bombsight. Whereas other methods are sensitive to correct determination of speed and altitude this latter method is relatively insensitive to errors in such factors.

The aircraft will not necessarily make a level approach to the target. On sighting the submarine the plane will normally be at a rather high search altitude and must lose altitude to make the attack.

Hence it is often natural for the plane to make the bombing run while still in a glide. In a glide attack the formulas for determining release point are somewhat more complex than in horizontal bombing, but similar methods of controlling range errors can be used. There is also the possibility of using the plane's motion in pulling out of a glide to release the bombs, a method known as toss-bombing.

Commonly used during the recent war, because of the lack of suitable bombsights, was the so-called seaman's eye method of bombing. This term is applied to bombing without a sight in which the pilot releases bombs at the proper moment by instinct gained over long periods of practice.

Aiming errors, for a given method of aiming, will vary widely with such factors as type of aircraft, degree of training and individual ability of pilots and bombardiers, conditions of attack, etc. It is not possible, therefore, to quote figures of general applicability. The performance of a typical TBF squadron trained in glide bombing at ASDevLant gives an indication of the order of magnitude of such errors in training and of the effect of practice in reducing them.

During a 3-week period, each pilot made about 100 practice attacks on a towed target, using a glide angle of about 15 degrees and aiming by means of a reflector sight. The mean point of impact (MPI) for all attacks was 62 ft over in range and 8 ft right in line. Probable error about the MPI was 80 ft in range and 30 ft in line.[a]

During the 3-week period the MPI in range decreased from about 135 ft to 18 ft. The MPI in line did not improve. The probable error about the MPI decreased from 98 ft to 40 ft in range and from 38 ft to 25 ft in line. It is evident, therefore, that training brought the MPI effectively on the target and reduced dispersion about the target very noticeably. Improvement was still continuing after 100 practice attacks per pilot.

After the 3-week training period in glide bombing the squadron spent a week in horizontal bombing by seaman's eye. The MPI was 31 ft over in range and 1 ft right in line, with probable errors about the MPI of 66 ft in range and 14 ft in line. Since these results were obtained after the extensive practice in glide bombing, a direct comparison of overall results by the two bombing methods is not fair, but it can be judged that range errors in horizontal bombing were about 20 per cent greater than in glide bombing while line errors were only about half as great.

The improvement possible by use of an accurate sight is suggested by the fact that tests at ASDevLant with the BARB (angular velocity) sight showed a probable error of only 16 ft in range. It was found that very little training was required. Similar improvement in rocket accuracy by use of proper sights is indicated by ASDevLant tests. Using the reflector sight with prescribed sighting allowance, mean deviation of about 10 mils in range was achieved by the best trained squadrons, the RASP (automatic vector) sight gave 8 mils, and toss-rocketing, 6.3 mils.

Operational errors usually proved considerably greater than those obtained in practice attacks. These will be discussed in the next section.

The effect of the three types of errors discussed above on the success of an attack can only be determined by considering such errors in connection with the lethality of a given weapon. We shall therefore next discuss weapon lethality and then illustrate the combination of attack errors and weapon lethality in determining a priori probabilities of success.

12.2.2 Weapon Lethality

From a general point of view, the concept of commanded volume discussed under surface craft attacks is applicable to aircraft attacks. For example, if a stick of depth bombs is dropped, each bomb will have around it a commanded volume constructed by the method previously given. The probability of success will be given by equation (1).

$$P = \iiint\limits_{\text{Commanded volume}} p(x, y, z)\, dx\, dy\, dz, \tag{1}$$

where the function $p(x,y,z)$ is the probability that the center of the submarine is at position x,y,z and is determined by the attack errors. The probability of a hit on the pressure hull by a salvo of rockets could be similarly determined; in this case the commanded volume of each rocket would be the solid generated by moving along the underwater trajectory of the rocket an area equal to the cross section presented by

[a] It should be noted that line errors varied materially with angle between aircraft course and target course. The MPI was on target for track attacks and 10 or 20 ft right for beam attacks, according to whether approach was from port or starboard. Probable error about the MPI was about 15 ft for track attacks and 10 ft for beam attacks.

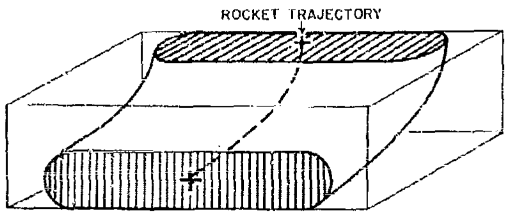


FIGURE 4. Commanded volume of antisubmarine rocket.

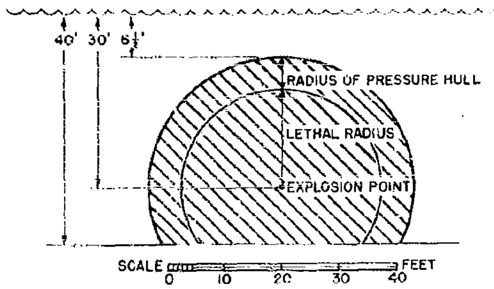


FIGURE 5. Depth coverage. Depth bomb, lethal radius = 17½ ft. Average width covered = 40 ft.

the pressure hull for the given angle of attack.[f] (See Figure 4.)

Because of the effect of blind time on bombing errors, however, aircraft attacks must be made on surfaced or nearly surfaced submarines to be successful. It is convenient, therefore, to eliminate submarine depth as a variable in the problem and to make probability calculations on the basis of an assumed depth or a small range of equally probable depths. This enables us to replace the concept of commanded volume by one of lethal area.

This method may be illustrated by considering an attack against a German 500-ton U-boat by an aircraft dropping a stick of depth bombs of the type used in World War II. For such attacks, a fixed depth setting of 25 ft was ultimately adopted. This is approximately correct for the average Class A submarine if we consider all depths of the pressure hull's center between 6½ ft (for surfaced U-boats) and 40 ft (for U-boats down 15 sec) as equally likely. Since bombs set for 25 ft actually exploded somewhat deeper, we shall assume an effective depth setting of 30 ft for our illustration. (This is probably about correct for the best United States fuze developed in World War II.)

Considering, then, only Class A attacks made with this effective depth setting and assuming all depths between 6½ ft and 40 ft as equally likely, the lethal area may be determined as follows. The average distance from the center of the pressure hull measured *perpendicular* to the submarine's keel within which a depth bomb must explode to be lethal is found from Figure 5. The bomb will be effective provided the center of the pressure hull lies within the shaded area of the diagram, that is, within a radius of the point of explosion equal to the lethal radius of the bomb plus the radius of the pressure hull. In the diagram, a lethal radius of 17½ ft has been used; this is about correct for a TNT-filled, 350-lb United States depth bomb. From this diagram the *average* width for which such a depth bomb is effective can be easily determined; it comes out as about 40 ft. In other words the charge must be at a distance, measured perpendicular to the keel, of not over 20 ft from the center of the pressure hull. Consider next the distance measured *parallel* to the submarine's keel within which such a bomb must explode to be lethal. For the 500-ton U-boat, allowing for variation in diameter at the ends and also for the fact that the charge may be effective somewhat ahead or aft of the hull, it is found that a bomb with a 17½-ft lethal radius should be effective if it explodes not more than 95 ft ahead or astern of the pressure hull's center, based on the same considerations as to depth as were previously used.

It follows, therefore, that for the kind of bomb and submarine considered there is a lethal area 190 ft long and 40 ft wide on the surface of the water with its center directly above the center of the pressure hull, as shown in Figure 6. Thus if a bomb explodes below this area at the assumed depth of 30 ft, it will sink the submarine.[g] The probability that this will occur depends, of course, on the attack errors.

Another point of view is to consider this lethal area as surrounding each bomb, with its long dimension in the direction of the U-boat's keel. Then if the center of the submarine lies within the lethal area of any one of the bombs of the stick, the attack will be

[f] Angle of attack is angle between aircraft course and submarine course.

[g] This is not strictly true of course, since there are bound to be fluctuations; some bombs will explode under the lethal area and fail to destroy the target, while others somewhat outside this area will succeed. The assumption of a fixed lethal area can, however, give us the correct average expectancy for a large number of cases.

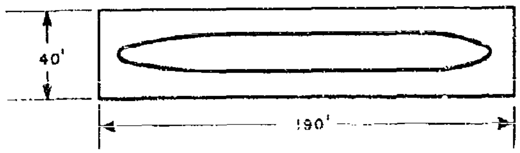


FIGURE 6. Lethal area for depth bombs (TNT filled 350-lb bombs).

successful. As before, the probability of this occurring may be found by consideration of the attack errors.

Similar methods of approach can be used for other types of bombs. The problem for rockets is also analogous. Under given conditions of submarine depth and angle of attack, considerations of the underwater trajectory of the rocket during the period for which speed is adequate for penetration will indicate how far short of the target, in range, it can strike and still be lethal.[h] The aspect presented by the submarine will determine permissible variation in line. For example, in a beam attack on a surfaced submarine with a 15° glide angle, it has been estimated that a Model 5 rocket will be lethal if it strikes the water not more than 67 ft short of the submarine nor more than 80 ft to either side; that is, under these conditions the lethal area is 67x160 ft, as shown in Figure 7.

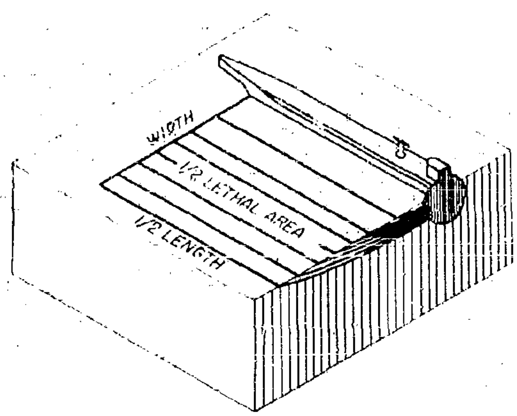


FIGURE 7. Lethal area for rocket against surfaced submarine (beam attack).

[h] Penetration of the pressure hull by a rocket may not always cause immediate sinking, but the resulting damage should normally be sufficient to keep the submarine on the surface and permit follow up attacks to sink it. Hence the term lethal may reasonably be used.

12.2.3 Probability of Success

We can illustrate the method of combining attack errors and weapon lethality to determine a priori probabilities of success by considering a stick of four depth bombs under the same assumptions as were used in our illustration of lethal area. For simplicity let us assume an attack made from directly on the beam and disregard individual dispersion of the bombs. We shall further assume that probable attack errors in range and line are 120 ft and 65 ft, respectively, and that these are normally distributed about the U-boat's center.[i] Under such assumptions it is evident that the most effective stick spacing is 40 ft, since with this spacing the lethal area of each bomb just touches that of each of the adjacent bombs and there are no gaps or overlaps in the total lethal area of the four bombs. We have, then, an effective lethal area for the whole stick of 160 ft along the aircraft's track and 190 ft perpendicular to the aircraft's track, as shown in Figure 8. If the center of the submarine lies within this total area the attack will be a success.

Based on the assumed probable error of 120 ft in range, the curve showing the probability that the center of the submarine will be a given distance *in range* from the center of the stick is simply the normal distribution curve shown in Figure 9. The probability that the center of the submarine will be within 80 ft of the center of the stick *in range* is, therefore, the area under this curve from $x = -80$ to $x = 80$, namely, 0.35.

A similar calculation of the probability that the center of the submarine will be within 95 ft of the center of the stick *in line*, based on the assumed prob-

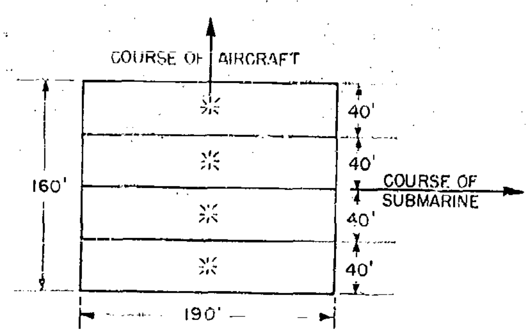


FIGURE 8. Area for stick of four depth bombs.

[i] These errors, considerably greater than those quoted earlier for practice drops, are still rather small for operational errors.

TABLE 2. Characteristics of bombs.

Type	Explosive	Nose	Lethal radius	Depth of explosion	Dispersion: Along aircraft course	Dispersion: Perpendicular to aircraft
350-lb depth bomb (explosive 250 lb)	TNT	Flat	17½ ft	30 ft	7 ft	7 ft
		Round	17½ ft	30 ft	17 ft	17 ft
	Torpex	Flat	22 ft	30 ft	7 ft	7 ft
650-lb depth bomb (explosive 450 lb)	TNT	Flat	25 ft	30 ft	7 ft	7 ft
		Round	25 ft	30 ft	17 ft	17 ft
60-lb contact (explosive 30 lb)	TNT	Flat	Contact	Contact	3½ ft	0

able error of 65 ft in line, gives 0.68. The actual probability of success depends on the occurrence of both these events and is therefore 0.35 × 0.68 = 0.24, in other words, under the assumptions made the stick of bombs has a 24 per cent chance of killing the submarine.

The calculation is considerably more complex if individual bomb dispersion is taken into account and if angles of attack intermediate between 0 degree and 90 degrees to the submarine's course are considered. The above example, however, illustrates the basic theory involved. We shall next examine the results of some a priori calculations of this sort.

Such calculations serve several purposes. They make it possible to determine optimum tactics for the use of a given weapon and answer such questions as: what is the best angle of attack, what is the best spacing for bombs in a stick, etc. More fundamentally, they make it possible to compare the expected effectiveness of different basic types of weapons and of different models of a given type. Such comparisons are of value in determining which weapons should be used and often suggest profitable improvements in their design. A priori probability calculations may also be used to study the effect of accuracy in the use of a given weapon and show to what extent improvement in probability of success is possible through improvement in accuracy. Finally, such calculations predict what should be expected from operational results and are useful in evaluating such results. We shall illustrate the above points by considering the use of bombs in Class A attacks against the German 500-ton U-boat with the same assumptions as to the depth of the pressure hull's center as were used in discussing lethal area (*i.e.*, all depths between 6½ ft and 10 ft are considered equally likely). Results will be shown for the basic types of United States bombs used in World War II. Table 2 summarizes the assumptions made as to their characteristics. (Weight is given in round figures; individual types of bombs vary somewhat in weight.)

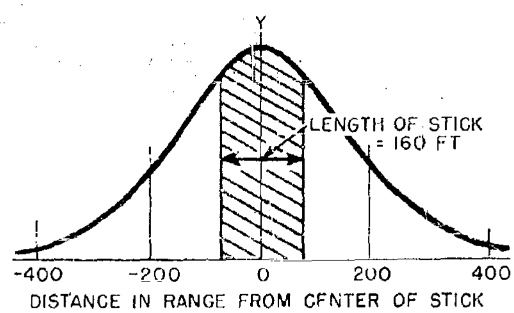


FIGURE 9. Probability that center of submarine will be a given distance in range from center of stick.

Assumptions as to probable aiming errors (including probable submarine position error) are shown in Table 3 for beam attacks and lengthwise attacks. (Consistent values have been used for intermediate angles of attack.)

On the above assumptions the effect of stick spacing on probability of success is illustrated in Figure 10 for 350 lb, TNT-filled, round-nose depth bombs. On the basis of similar calculations for various angles of attack, the curves shown in Figure 11 can be obtained. It will be noted from Figure 11 that there is a

TABLE 3. Assumed bombing errors for Class A attacks.

	Probable error in range	Probable error in line
Beam attack	120 ft	65 ft
Lengthwise attack	135 ft	20 ft

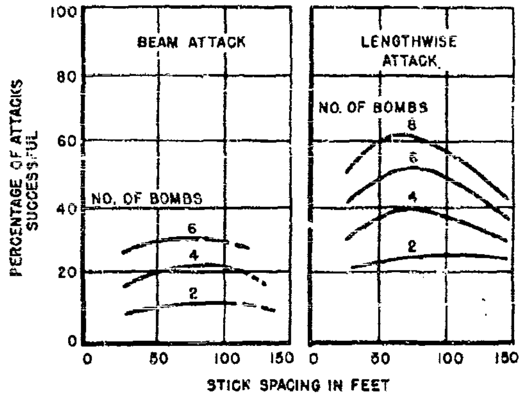


FIGURE 10. Probability of sinking as a function of stick spacing. 350-lb. round-nose depth bombs. TNT-filled.

wide variation in optimum spacing for a two-bomb stick according to angle of attack and only small variation for other stick sizes. Figure 10, however, shows that the actual effect of stick spacing on probability of success is almost negligible for a two-bomb stick and is greatest for the longer sticks. In other words, for cases where the optimum varies, the importance of using the optimum value is small, whereas for cases for which use of an optimum value is important nearly the same value is optimum for all angles of attack. It follows therefore that an overall value of about 75 ft for all angles is quite satisfactory.

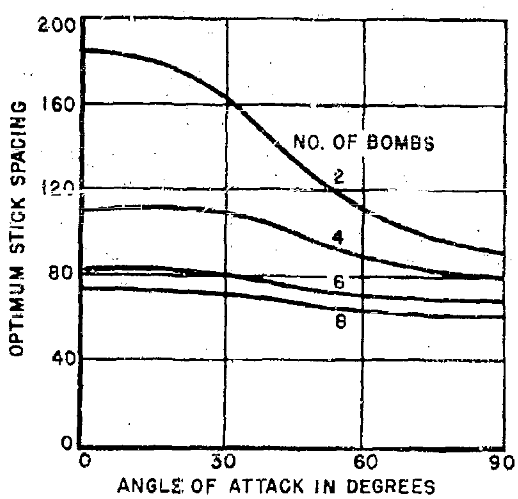


FIGURE 11. Optimum stick spacing as a function of angle of attack. 350-lb. TNT-filled, round-nose depth bombs.

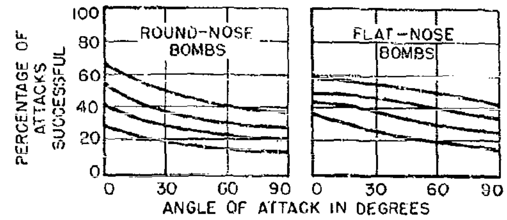


FIGURE 12. Probability of sinking as a function of angle of attack, with best stick spacing for each angle.

This is an important conclusion, since varying the stick spacing for each attack would result in complication and delay. It can also be seen from Figure 10 that even for larger sticks the use of values deviating somewhat from the 75-ft value suggested will be quite acceptable. (Similar conclusions have been found for flat-nose bombs.)

The effect of angle of attack on success is illustrated in Figure 12 for the round-nose depth bombs just considered and for corresponding flat-nose bombs. It is apparent that angles along the submarine's track give the best probability of success. The improvement possible by selecting this angle makes it worthwhile to do so wherever convenient. However, the gain is not sufficient to warrant delay in attack for this purpose.

The above results are merely illustrative since the effect of stick spacing and angle of attack will vary with the type of bomb considered and the assumptions made in the calculations, but it is felt that the conclusions may safely be applied to low level depth bomb attacks on Class A submarines. We shall now proceed to a comparison of the different types of bombs listed in Table 2, averaging results over all angles of attack and using the best stick spacing at each angle.

Such a comparison is most instructive if made on a weight-for-weight basis, as has been done in preparing the curves shown in Figure 13.

One fact is immediately evident from these curves. There is a great gain in effectiveness with number of bombs dropped, regardless of type. This means that it is important to drop a sufficient number in the first attack to secure a high probability of success. Withholding bombs is not warranted unless there is a very good chance of making a second Class A attack. For example, if the chance of a second attack is less than 25 per cent, as many as ten 350-lb bombs are justifiably expended on the first attack.

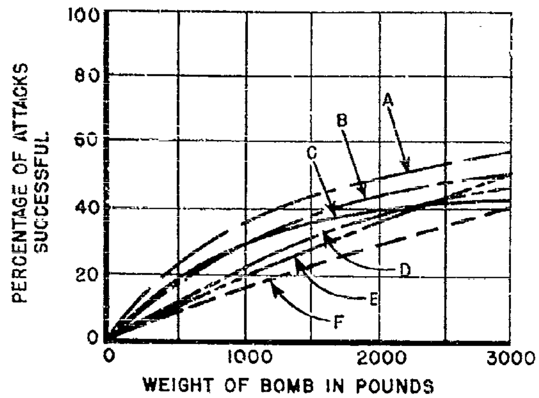


FIGURE 13. Probability of sinking as a function of weight of bombs in stick for various types of bombs. Averaged over all angles of attack with optimum stick spacing at each angle. *A* 350-lb Torpex flat nose; *B* 350-lb TNT flat nose; *C* contact; *D* 350-lb TNT round nose; *E* 650-lb TNT flat nose; *F* 650-lb TNT round-nose.

A comparison of the results according to type of bomb illustrates several important points. These may be summarized as follows.

1. A comparison of the curves for round-nose bombs with the corresponding curves for flat-nose bombs indicates the marked improvement achieved by decreasing the dispersion in underwater trajectories of individual bombs from 17 ft to 7 ft through proper design of the bomb.

2. A comparison of the curves for 350-lb bombs with those for 650-lb bombs shows that on a weight-for-weight basis the smaller bombs should be markedly superior for all sizes of bomb stick. Although the 350-lb depth bomb is the lightest used by the United States Navy, it is not necessarily optimum. A study, under the same assumptions, of the British 265-lb bomb (weight of Torpex, 193 lb) showed somewhat better results on a weight-for-weight basis. It is quite possible that still lighter bombs might be effective, but the results would depend on various factors, such as the percentage of explosive weight to total weight, weight of equipment required to drop longer sticks, etc.

3. A comparison of the curve for the 350-lb Torpex flat-nose bomb with the curve for the corresponding TNT-filled bomb shows the value of using a more powerful explosive. Improvement of lethal radius for a given weight of bomb by means of an improved explosive is a very effective means of increasing the lethality of attack.

4. The curves show that for the bombs considered (and under the assumptions made) the 350-lb flat-nose, Torpex-filled depth bomb is superior for any given weight of bombs dropped. For the other types, the contact bomb of Hedgehog type appears superior for weights under about 1000 lb, but this may be only an apparent advantage. Depth bombs exploding outside lethal range may still damage the submarine, whereas a near miss with a contact bomb does no damage. Furthermore, the extra weight required by more numerous bomb racks for small contact bombs will also lessen their advantage. Since only Class A attacks have been considered, it may seem that the advantage of contact bombs in covering all possible submarine depths has been disregarded in our analysis. Actually, however, consideration of later attacks would add little to the probabilities for contact bombs because of the uncertainty of submarine position.

The above results are based on fixed assumptions as to aiming errors. The effect of such errors is illustrated in Figure 14 for a stick of six 350-lb Torpex flat-nose depth bombs. Probability of sinking has been averaged over all angles of attack with best stick spacing for each angle. Results are shown according to the probable range error for a beam attack. Line errors for beam attacks and both line and range errors for other angles of attack have also been varied so as to be proportional to the range error indicated, using the relationship reflected in Table 3. This curve shows very strikingly the importance of accuracy in aiming. For range errors under 50 ft, an attack is almost certain to be successful, but the prob-

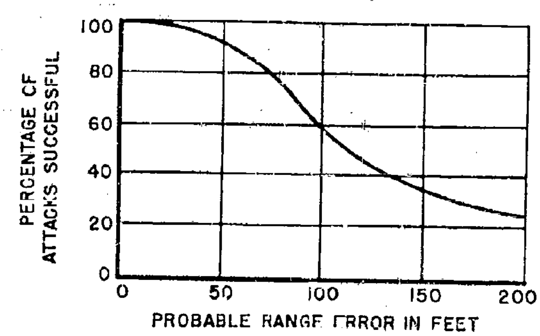


FIGURE 14. Probability of sinking as a function of the expected errors in bombing for six 350-lb Torpex flat-nose depth bombs.

TABLE 4. Effect of degree of submergence at attack. (Independent attacks by United States aircraft.)

Degree of Submergence	July–Dec 1942 No.	July–Dec 1942 % A–D	July–Dec 1942 % A or B	Jan–July 1943 No.	Jan–July 1943 % A–D	Jan–July 1943 % A or B
Fully surfaced	17	11	24	52	37	23
Decks awash	7	29	0	5	40	20
Stern and/or conning tower	22	32	5	25	20	4
Periscope	3	0	0	2	0	0
Down 0–15 sec	38	3	3	11	18	9
Down 15–30 sec	25	4	4	11	0	0
Down 30–45 sec	12	0	0	4	0	0
Down over 45 sec	22	0	0	5	0	0
Other	9	8	8	33	30	21
TOTAL	167	5	5	150	25	15

ability drops off rapidly thereafter. For errors of about 125 ft it is down to about 50 per cent. The value of an effective bomb sight is clearly indicated by these figures.

A priori probabilities of success with eight solid-head rockets, for effective angles of attack, are of about the same order of magnitude as corresponding probabilities of success with six depth bombs using the seaman's eye method of aiming. For example, using aiming errors (standard deviation) of 35 mils in azimuth and 25 mils in elevation (which are about twice the errors obtained in practice), the probability of a kill on a Class A U-boat at 400 yd range in a 20 degree dive with eight rockets is about 50 per cent. This is about the same as the probability shown in Figure 14 for six United States Torpex flat-nose depth bombs with a range error of 120 ft. The above comparison, of course, involves certain specific assumptions as to aiming errors and weapon characteristics. Future improvement in aiming methods and, possibly, in weapon design may affect the two weapons differently and it is, therefore, not possible to conclude which will ultimately be the better. Actually, it is not necessary to decide this point since they are complementary in nature. Depth bombs are effective at all angles of attack and for attacks made shortly after submergence, while rockets are restricted to angles near the beam and to use on visible submarines. On the other hand, rockets are light in weight and provide an effective weapon for small planes which cannot carry bombs. They also provide an additional punch for bombing planes, giving them something like twice the effective weapon capacity with only a small increase in load.

12.3 OPERATIONAL EXPERIENCE

Actual results achieved in aircraft attacks during World War II verify many of the a priori conclusions drawn in the previous section. First to be considered is the importance of making prompt attacks and of using a depth setting appropriate for such attacks.

12.3.1 Effect of Degree of Submergence at Attack

Table 4 shows the results achieved by independent United States aircraft attacks in the Atlantic and Mediterranean during the last half of 1942 and the first 7 months of 1943. The percentage of A–D attacks (U-boat sunk or damaged) and that of A or B attacks (U-boat sunk or probably sunk) are shown for each period according to the degree of submergence at attack.

The marked improvement in overall results from the first period to the second is clearly associated with a much greater proportion of attacks on fully surfaced U-boats. The detailed breakdown for each period shows quantitatively the correctness of the conclusion reached in our theoretical discussion as to the decrease in probability of success with increase in degree of submergence.

12.3.2 Importance of 25-ft Depth Setting

When the United States entered World War II, depth settings of 50 ft were common. By the latter half of 1942, the importance of a shallower setting had been recognized and the usual depth setting was

25 ft. However, 39 attacks during July–December 1942 involved 50-ft settings. These resulted in 3 per cent A–D assessments as compared with the overall figure of 11 per cent shown in the above table. During the first half of 1942, when the deeper setting was generally used, a total of 171 independent aircraft attacks on U-boats in the United States Strategic Area resulted in only 4.6 per cent A–D assessments. Undoubtedly the deeper setting was at least partly responsible for this poor showing. Operational experience thus bears out clearly the importance of making prompt attacks with a shallow depth setting.

Since the 25-ft setting for United States depth bombs actually produced explosion at depths greater than 25 ft on the average, the improvement noted above was only a partial realization of that which was theoretically possible. Tests indicated that during the period January–July 1943 the current United States depth bomb when set for 25 ft actually fired at depths between 27 and 64 ft, with an average of about 40 ft. On the other hand, the British depth bomb fired at very nearly the correct depth. A comparison of operational results with the two different bombs should therefore indicate the advantage of the one which exploded at the desired depth. Such a comparison is made in Table 5. The British figures are based on daylight attacks on fully or partly surfaced U-boats during the period April–October 1943. The United States figures are based on attacks for the period January–July 1943, including all degrees of submergence. To compensate for the inclusion of attacks on submerged submarines, United States attacks assessed A–D (sunk or seriously damaged) are considered successful. (Since 72 per cent of the United States attacks were on fully or partly visible U-boats, whereas kills were only 54 per cent of the total A–D assessments, this actually results in overcompensation, and the comparison is therefore somewhat too favorable to the United States depth bomb.)

TABLE 5. Operational results with different depth bombs.

British depth bomb

Theoretical results		Operational results		
No. of bombs	Per cent kill	No. of bombs (average)	Per cent kill	Ratio of operational to theoretical
2	20.5	2.5	20	98%
4	34	4	28	82%
6	51	5.9	37	73%
8	57	7.8	55	96%

United States depth bomb

Theoretical results		Operational results		
No. of bombs	Per cent kill	No. of bombs (average)	Per cent kill	Ratio of operational to theoretical
2	23.5	2.4	4	17%
4	41.5	4	27	65%
6	54	5.7	33	61%
8	66	8.3	36	55%

It can be seen from the above that the British bomb gave results close to expectation, whereas the United States bombs averaged a little over half the expectation.

12.3.3 Importance of Bombing Errors

Next to be considered are operational bombing errors and improvement in them due to practice and the use of bombsights. As to the actual size of such errors a British analysis of 48 photographed daylight attacks made by seaman's eye on visible submarines during the period March–October 1943, showed mean errors about the conning tower of 141 ft in range and 71 ft in line. These errors were not uniformly distributed about the conning tower. Systematic errors in estimating submarine motion were apparently negligible but there was a systematic overshoot along the aircraft track resulting in an MPI which was 86 ft over in range. The MPI in line was reasonably near the conning tower, i.e., 13 feet left. The errors showed considerable variation with angle of attack; the measured results are shown below. It was found that the photographic sample was biased since track attacks with small line error rarely gave satisfactory photographs because explosion plumes obscured the U-boat. Therefore, the line error in track attacks shown in Table 6 is somewhat too large. Attacks on submarines which had submerged less than 15 sec before attack gave average errors of 192 ft in range and 73 ft in line. The sample, however,

TABLE 6. Operational bombing errors (visible U-boats).

	Average line error (feet)	Average range error (feet)
Beam	75	121
Quarter	75	155
Track	66	139

was small and results are not very reliable. Comparison of these measured errors with those assumed in Table 3 for theoretical calculations shows reasonable agreement, with the assumed errors somewhat smaller than those actually made in operations.

The effect of practice in reducing bombing errors cannot be evaluated explicitly from operational results because of the lack of sufficient photographs. The importance of continued practice is, however, illustrated by Coastal Command experience for the period May-December 1943. Table 7 shows a comparison of results for this period according to amount of practice.

TABLE 7. Effect of practice on attack accuracy.

	Bomb aimers who had dropped less than 10 practice bombs during preceding month	Bomb aimers who had dropped more than 10 practice bombs during preceding month
Good attacks	51%	65%
Moderate attacks	13%	20%
Bad attacks	36%	15%

The effect of a bombsight on bombing accuracy is illustrated by British experience with the Mk III (angular velocity) sight. An analysis of results through June 1944 showed average range errors about the conning tower of 130 ft as compared to 180 ft for seaman's eye bombing under the same conditions. Average line errors were 53 ft as compared to 56 ft by seaman's eye, though there is no reason to expect an improvement in line error. There was an increase in lethality of about [illegible] per cent in kills and 60 per cent in kills and damage. These results are based on a very small sample (32 attacks, 16 photographs) and therefore are not conclusive; however they do show the bombsight to be a promising development.

12.3.4 Importance of Large Bomb Stick

Operational experience has clearly borne out the advantage of dropping large sticks of bombs. For example, in the period from July 1942 to July 1943 United States results for depth bombs set at 25 ft were as given in Table 8.

TABLE 8. Success of attack for different sizes of stick. (United States aircraft, July 1942–July 1943.)

Number of bombs	Percentage A–D assessments
1–3	13
4	21
5–12	31

12.3.5 Results with Rockets

Operational results with rockets are not very extensive. Almost all United States rocket attacks were made in connection with other types of attacks so that no specific conclusions can be drawn from them. British attacks, however, demonstrate that rockets have been effective. For example, during the period May-December 1943, 18 attacks on Class A U-boats (of which 11 were fully surfaced) resulted in 33 per cent A or B assessments and an additional 22 per cent C, D, and E assessments. The 33 per cent kills is in fair agreement with the 50 per cent expected figure quoted in our theoretical discussion when consideration is given to the fact that the average firing range was 600 yd instead of 400 yd, the average number of projectiles 7.3 instead of 8, and the average glide angle 17 degrees to 25 degrees instead of 20 degrees. The above figure of 33 per cent kills is comparable to the result previously shown for British depth-bomb attacks on visible submarines, using six bombs, for the period April-October 1943, namely 37 per cent. (See Table 5.) It is the same as the figure previously shown for six United States depth bombs (based on A-D assessments, all attacks). There seems little doubt, therefore, that rockets are of about the same degree of effectiveness as depth bombs, although, as pointed out previously, each weapon has its own particular advantages.

Chapter 13

OFFENSIVE SEARCH

PREVIOUS CHAPTERS have discussed problems involved in the defense of ships and convoys and in attacks on submarines by surface craft and aircraft. To some extent these attacks may be made on submarines contacted during escort of convoy operations, but these operations are not the only source of contacts. Normally, offensive operations are also undertaken for the specific purpose of contacting and attacking submarines in order to inflict a high loss rate on the enemy submarine fleet. While the overall aim of all antisubmarine operations is a negative one—to prevent the submarines from accomplishing their objective—this aim can be achieved by both defensive and offensive means. Convoy escort is clearly defensive, but once convoy escorts make a contact, an effort is made to attack and sink the sub, that is, to take the offensive. Sinking the submarine is valuable in a direct defensive way in that it is then certainly prevented from attacking the convoy, but a sinking is also valuable offensively in that the submarine is thereby eliminated from all future operations. The clearly offensive phase of antisubmarine activity takes the form of searching for submarines and attacking them even when they do not immediately threaten any friendly ships. The distinction is not absolutely hard and fast, since any submarine is a potential threat. Defensive measures are intended to find and attack submarines that may be dangerous within the next few minutes or hours, offensive measures, those dangerous at more remote time.

Methods for attacking submarines are the same whether the intent is offensive or defensive, but the methods involved in searching for a submarine depend on the aim of the operation. In particular, defensive operations are carried out fairly close to the ships being defended, whereas offensive operations are concentrated in the regions containing the most subs, other things being equal. This chapter will outline some of the considerations involved in conducting offensive searches. Three general types of situation are involved.

1. *Search of an area* in which one or more submarines are thought to be patrolling.

2. *Interception of submarines* in transit whose paths are thought to pass through a certain region.

3. *Follow-up of contacts* made some time previously and then lost, for the purpose of finding the submarine again.

These problems have been discussed in general terms in Volume 2B, *Search and Screening*, Chapters 3, 7, and 8, but not with special reference to searching for submarines. In these chapters detailed methods are described for designing searches in a great variety of tactical situations, and the basic theory of search is developed, which applies to search for submarines as a special case. Consequently the following discussion is, in a sense, a review of material presented in *Search and Screening*, with emphasis on the antisubmarine applications and operational data reflecting experience in antisubmarine warfare [ASW].

13.1 SEARCH OF AN AREA

When available intelligence indicates[a] that submarines are on patrol in a certain region, search for them will be productive of contacts in proportion to the density of submarines and to the area which can be covered by the searching craft. The general considerations of Chapter 3 of *Search and Screening* apply, assuming the available intelligence to be expressed as a probability density function. For a given function $p(x,y)$, the chances of success are determined by the search rate and the amount of searching effort available. In order to have an effective search the searching craft must either be many in number or have a large sweep rate.

13.1.1 Aircraft Search for Surfaced Submarines

Aircraft are outstanding for having a large sweep rate because of their high speed and distant visual horizon.[b] They are normally restricted to visual and radar detection, however, and are thus effective only

[a] While the accuracy of intelligence is of great importance in deciding on the plan of any search operation, since it determines the area that should be searched, analysis of the accuracy of different types of intelligence is beyond the scope of this discussion.

[b] See Chapters 4 and 5 of Volume 2B, *Search and Screening*.

against surfaced (or Schnorcheling) submarines.[c] Consequently the density which must be used in studies of aircraft search is the density of surfaced submarines, and a region in which there are many submarines all of which are submerged is not profitable for search by aircraft.

As an example of the influence of the submarine's submergence tactics, the offshore gain effect can be used to illustrate the significance of sweep rates. It was common experience that aircraft patrol was relatively most effective when carried out at a considerable distance from shore bases, since submarines close to them were cautious and spent a large fraction of the time submerged. As an example of the phenomenon, data based on Moroccan Sea Frontier flying are of interest.

The region under study was divided into zones 200 miles wide, that is: 0–200 miles from land, 200–400 miles, 400–600 miles, and 600–800 miles. The number of actual aircraft contacts in each zone was counted, and an expected number computed, which was based on the number of flying hours in each zone, the total density of U-boats in the zone, and an assumed 5-mile sweep width. In this way the figures of Table 1 were derived. The effective sweep width is

TABLE 1. Contacts in Moroccan sea frontier antisubmarine patrols.

Distance from base (miles)	0–200	200–400	400–600	600–800	Total
Expected No. contacts	83	58	30	20	191
Actual No. contacts	5	5	10	6	26
Per cent realized	6	9	33	30	14
Effective sweep width (miles)	0.3	0.5	1.6	1.5	0.7

the value of sweep width that would have to be used in computations to have the expected number of contacts equal to the number actually obtained. The increase in effective sweep width or "per cent realized" as distance from shore bases is increased is probably due to a relaxation of precautions by the U-boats. Whatever its cause, however, it is evidence of the desirability of flying at considerable distance from shore bases when on offensive patrol.

The use of radar to increase the sweep width beyond that achievable by visual means is of great importance in area search (or in any other type). Early radars did not have a detection range sufficiently great to exceed that of visual detection except in periods of darkness or low visibility, but the newer types are powerful enough to do so a large part of the time. The older radar was valuable chiefly because it made contacts in periods of low visibility when U-boats were surfaced. Data on Army Air Forces Anti-Submarine Command flying in Eastern Sea Frontier for May through October 1942 and in the Trinidad area for October and November both bear this out, as is shown in Table 2. In these cases

TABLE 2. Radar versus visual search during 1942 (in terms of hours per contact).

	Visual only	Radar during day	Radar during night
ESF May–Oct			
Hours of flying	21,108	1,665	1,125
No. of contacts	32	10	7
Hours per contact	660	166	161
Trinidad Oct–Nov			
Hours of flying	1,100	2,100	130
No. of contacts	3	1	9
Hours per contact	170	600	50

use of radar during the daytime did not do very much to reduce the number of flying hours required to secure a contact, but radar used at night was many times more effective than in daytime. The chief explanation is, no doubt, that U-boats were submerged in these regions during the daytime and good opportunities for contacting them were offered only at night.

Patrol height is also of importance in achieving the maximum sweep rate. For both visual and radar search the altitude must be sufficiently high to give a distant horizon, and for visual search the increased apparent area of the wake is also of importance, as explained in Chapter 1 of Volume 2. The theoretical

TABLE 3. Sweep widths for aircraft visual search. (Surfaced submarine under way.)

Altitude (feet)	Visibility 3 miles	Visibility 15 miles
500	3.0	8
1,000	3.5	10
2,000	3.5	11
5,000	...	12
10,000	...	11

[c] Special gear in the form of sonobuoys or *magnetic anomaly detectors* [MAD] are available for detection of submerged submarines. They will be discussed later, since the sweep rates are very small.

table of sweep rates presented in Table 3 shows clearly the advantages of high altitude for visual search.

As an example of operational data confirming the value of flying at fair height, data on sightings in the Bay of Biscay area during May 1943 can be quoted. Table 4 gives the sightings per 100 sorties. As would be expected, altitudes over 2000 ft give only a slight gain when meteorological visibility is low but have considerable advantage under good visibility conditions.

The question may well be raised, however, whether the high altitude is not a handicap in delivering an attack. The aircraft must lose altitude to make a low-level bombing run, which would sometimes slow up the approach. The overall results shown in Table 5 do not, however, indicate any significant effect of this sort. It is probable that U-boat

TABLE 4. Sightings per 100 sorties for different patrol heights.

	Meteorological visibility		
Height of patrol	0–4 miles	5–12 miles	over 12 miles
0–2,000 ft	6.2	14	22
Over 2,000 ft	7.9	26	37

TABLE 5. Effect of altitude on success of attacks.

Height of patrol (feet)	Percentage of Class A attacks (Coastal Command data, June–Nov 1943)			Per cent of attacks causing damage (U. S. Strategic Area July–Dec 1942)		
	Total No. sighting	No. of Class A	Per cent Class A	Total No. attacks	No. assessed A–D	Per cent A–D
0–2,000	96	44	46	91	10	11
2,000–4,000	86	34	40	36	3	8
Over 4,000	38	18	47	32	3	9

lookouts have tended to scan the horizon in search for aircraft so that the higher flying aircraft have somewhat of an advantage in approaching undetected. In any event the overall gain of altitude above 2000 ft is clear.

There are many other questions relating to the most effective conduct of visual or radar search of a submarine patrol area by aircraft. The general problem involved is to achieve the best possible sweep width and then lay out a patrol where surfaced submarines are densest in accordance with Chapters 3 and 7 of Volume 2B, *Search and Screening*.

The advent of Schnorchel drastically reduced the aircraft's search capabilities because both radar and visual sweep width on Schnorchel are much less than on surfaced U-boats according to most estimates only 1/10 to 1/100 as great. To a slight extent this reduction is compensated by the Schnorcheling U-boat's need to operate in restricted focal areas, the area to be searched by either aircraft or surface craft being thus much reduced. A net result has been a marked increase in the importance of surface craft search compared with that by aircraft for submarines operating on Schnorchel.

To some extent however, aircraft can conduct a sonar search by use of sono-buoys. If the submarine is proceeding at high speed on Schnorchel and is therefore noisy, the effective sweep rate of a group of sono-buoys monitored by an aircraft may be comparable to that of surface craft using sonar.

12.4.2 Surface Craft Search and Submerged Submarines

The role of surface craft in searching an area is limited by their small sweep rate. Visual and radar detection ranges are shorter than for aircraft, and the speed of the ship very much less. Table 6 presents a

TABLE 6. Sweep rates under various conditions (in sq miles per hour).

	Surfaced sub	Submerged sub
Aircraft		
Visual (good visibility)	1,250*	Approx 0
Radar (ASG)	2,500	Approx 0
MAD	25*	15–20*
Sono-buoys	200*	15*
Surface craft		
Visual	Approx 0	Approx 0
Radar (10 cm)	100	Approx 0
Sonar	15	15

* Estimated on the basis of tests but not confirmed by operational data.

comparison of typical aircraft and surface craft sweep rates. Visual search by surface craft is not likely to be effective since the submarine can almost invariably see the surface craft in time to dive before the surface craft sees it. This visual search has purely hold-down value and is not effective in an offensive sense. Radar search by surface craft under low visibility conditions may, on the other hand, be expected to lead to contacts on any surfaced submarines unless they are fitted with search receivers and dive upon being approached. For surfaced submarines, however, the surface craft have a considerably smaller sweep rate than aircraft, so that the chief role of surface craft is conducting searches for submerged subs, a task for which aircraft are not effective.

The sweep rates for aircraft using *magnetic anomaly detectors* [MAD] or sono-buoys in hunting submerged submarines are about the same as that for surface craft using sonar, according to Table 6. The comparison is not a completely fair one, however. In the first place, the aircraft figures are based on trial results and have not been completely substantiated by operational data. Operational experience has indicated that classification of MAD and sono-buoy contacts is particularly difficult. In the second place, neither of them gives an accurate determination of the submarine's position but only a general indication of its presence, and it is difficult to make an effective attack on contacts of this type.

The primary task of surface craft in area search is thus sonar search for submerged submarines. Such search can be effective only if the submarines are concentrated in a small area, since the surface craft sweep rate is so small. To search an area 100 miles square with five ships requires about 6 days, whereas a single aircraft can search the same area for surfaced subs in 4 hours. Accordingly there are relatively few circumstances in which surface craft can be employed profitably for area search.

To some extent high-frequency direction finding [DF] extends the search capabilities of surface craft, since it enables the ship to take a bearing on a submarine transmitting on high frequency within about 20 or 30 miles. If the submarines transmit frequently, as German U-boats did during the height of the Battle of the Atlantic, DF can increase the radar sweep rate by a factor of up to 3 or 4 for surfaced subs. A DF contact is not quite so valuable as a radar contact, however, because it is less definitely localized and more difficult to convert into an attack.

Fundamentally, then, surface craft search of an area is a matter of sonar search. World War II has not offered very many opportunities for such search, surface craft having been put to effective use mainly in follow-up of contacts and in defensive operations, and consequently little in the way of operational data is available.

One tactical principle should be emphasized, however, that of searching in groups in line abreast. The theoretical reason for doing this is that a submarine has a good chance of evading a single ship by steering to one side at high speed when the approach of the ship is detected. Figure 4 shows the effect of such eva-

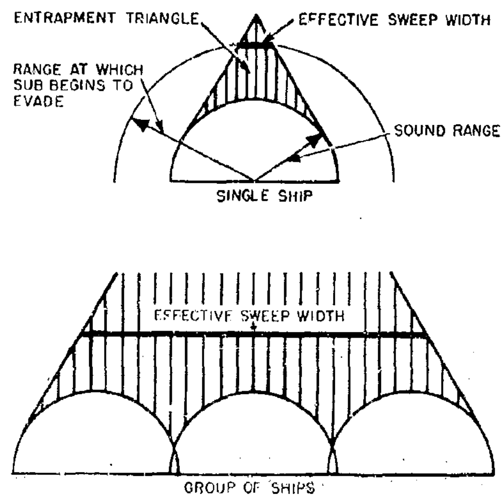


FIGURE 4. Submarine evasion of sonar search.

sion. The "entrapment triangle" is drawn tangent to the sonar detection circle with limiting escape lines drawn at angle = $\sin^{-1}$ sub speed/ship speed. In this way it is analogous to the submerged approach zone except that the submarine is trying to get out rather than in. As can be seen from Figure 4 searching in line abreast makes such evasion impossible except from positions near the ends of the line. Some theoretical considerations concerning search in line abreast are given in Chapter 6, Volume 2B.

There are also many practical reasons for searching in line abreast. The ships are close enough for convenient communications and know the positions of their fellow ships at all times. Similarly the ships are readily recognizable by aircraft or other forces in the area, even at night. In addition ships are in a posi-

tion to coordinate during attack once a contact is made.

It is, in fact, almost always valuable to carry out offensive operations in groups. If a group of units is sent out at once on parallel sweeps (or to patrol the same area according to some fixed plan), any unit making contact has immediate assistance available (provided communications are satisfactory), and all the other units can, if desired, enter into the process of attacking or following up the contact. In this way the chances of sinking the submarine, once contact is made, are very materially increased over what they would be with a single attacking unit. As a balance to this gain is the necessary loss in probability of making contact which results from concentrating too much of the searching effort into a particular area or period of time to the exclusion of some others. These two considerations must be weighed and the best compromise achieved. When the area to be searched is rather large, however, as is usually the case, a search by a group of units covers it only very incompletely and there is no difficulty with "over-searching." In such a case offensive patrol in groups spaced as closely as possible without overlapping of the areas searched by individual units is clearly desirable. Groups may involve aircraft or surface craft, or both. The basic idea is simply to provide for coordinated attack upon any contact that is made without appreciable loss in efficiency of distribution of search effort.

13.2 INTERCEPTION OF TRANSITS

In many cases it is profitable to endeavor to intercept submarines en route to their patrol area and attack them before they are able to become dangerous. Submarines in transit may be thought of as making up a moving density distribution (as opposed to a stationary one for those on patrol). This comparison is discussed in detail in Chapter 7 of Volume 2B and the appropriate modifications in search plans are described. As a result of this movement, the crossover type of barrier patrol is usually the most efficient, as was pointed out in Volume 2B.

This movement does not, in itself, make detection of the submarines involved any easier but often results in a more accurate estimate of the submarine's position than is possible with a submarine on patrol. This may be very strikingly true if the submarines are constrained to pass through a relatively narrow region while on passage to the patrol area. In such a case the submarine density is much higher in the transit area than the patrol area and consequently the former is the better area for exploitation by an antisubmarine offensive, other things being equal.

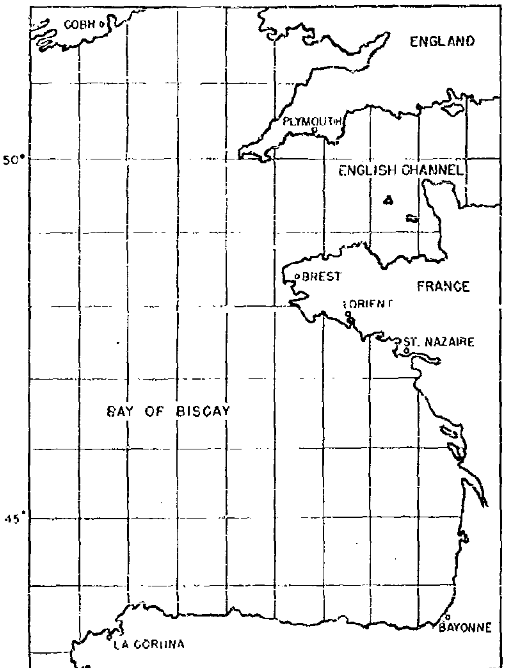


FIGURE 2. Bay of Biscay.

13.2.1 The Bay of Biscay Offensive

The outstanding transit area of this type has been the Bay of Biscay off the U-boats' French ports of Brest, Lorient, St. Nazaire, and La Pallice. All U-boats entering or leaving these ports had to funnel through the Bay within reach of British-based air cover, so that excellent opportunities for attacking U-boats were presented. (See Figure 2.)

An analysis of the possibilities of an offensive in the Bay was made late in 1942,[d] some of whose salient arguments are discussed here. The basic idea was that the U-boats had to spend a fair amount of time on the surface crossing the Bay and that therefore a "balanced" force capable of carrying out effective search both day and night would be able to intercept

[d] Operations Research Section, Coastal Command, Report No. 204, *Air Offensive Against U-Boats in Transit*, December 10, 1942.

a large fraction of the U-boats and inflict very serious losses. (Schnorchel was not to appear until long after this time.) By adopting maximum submergence tactics, the U-boat could reduce its time on the surface during any given day very greatly, but a greater number of days was required to cross the Bay because of the slower speed involved, and the entire passage could not be made submerged. The net gain by submerging is shown in Table 7, assuming a 300-mile band covered by aircraft across which the U-boats must pass. Thus the U-boat must spend about 13 hr on the surface in crossing the Bay even when using maximum submergence.

TABLE 7. Surfaced days per transit.

Fraction of time spent on surface (per cent)	Speed on surface (kt)	Speed submerged (kt)	Average speed (kt)	Total time (hours)	Time on surface (hours)
100	10	.	10	30	30
50	10	1.5	7.2	42	24
20	10	2.8	4.2	71	14
10	10	1.5	2.4	125	13
100	17	.	17	18	18

If the total number of transits per month is designated by τ, then the average number of surfaced U-boats in the area is (there being approximately 720 hr per month):

$$N_s = \frac{13}{720}\tau. \tag{1}$$

The expected number of contacts is

$$N = Qh\frac{N_s}{A} \tag{2}$$

where Q = aircraft sweep rate,
h = number of flying hours per month,
A = area involved.

In order to contact every transit U-boat once, for example, it would be necessary to have $N = \tau$, which condition can be used with equations (1) and (2) to determine the number of flying hours required.

$$\tau = \frac{Qh}{A}\frac{13}{720}\tau,$$

$$h = \frac{720}{13}\frac{A}{Q} = 55\frac{A}{Q}. \tag{3}$$

The area involved is about 300 miles square so that the hours required are as given by Table 8.

TABLE 8. Flying requirements to sight each transit.

Type detection gear	Sweep rate Q (sq miles per hour)	Flying hours per month required
Meter-wave	800	6,000
Centimeter	2,800	1,800

These figures for flying hours per month can readily be interpreted in terms of the number of planes required. A long-range plane is normally capable of flying about 50 hr per month, so that a force of about 40 such planes equipped with centimeter radar would be adequate to contact each U-boat crossing the Bay. (The flying required to get back and forth from base to the active Bay area would not increase this figure greatly.)

The comparison of actual results obtained in the operations with these predictions is of particular interest. Since the situation changed rapidly from time to time the data presented in Table 9 are given by months and divided into three periods corresponding to various stages of the battle. Average values are given for each period. At the end of the third period the number of transits dropped off sharply and U-boat activity did not again reach the previous level.

TABLE 9. Results of Bay of Biscay offensive.

Month	Flying hours on patrol	U-boat transits	Sightings of U-boats	Per cent sighted
First period				
June 1942	2,600	50	26	52
July	3,750	65	20	31
Aug	3,200	80	37	46
Sept	4,100	90	39	43
Average	3,100	71	30	43
Second period				
Oct 1942	4,100	95	18	19
Nov	4,600	110	19	17
Dec	3,400	130	14	11
Jan 1943	3,730	105	16	10
Average	3,800	117	15	13
Third period				
Feb 1943	4,400	100	32	32
Mar	4,600	135	42	31
Apr	4,200	115	52	45
May	5,350	120	98	81
June	5,900	57	60	105
July	8,700	78	81	104
Average	5,500	101	61	60

The first period involves night flying by Wellingtons equipped with Leigh Lights and meter-wave radar. Only about 10 aircraft were so equipped, but the overall result was to sight almost half the transits. Since the number of flying hours per month was only slightly more than half that quoted in Table 8 for meter-wave radar, this result is not far removed from that predicted. Actually the predicted average number of sightings would be 40, the operational results 30—a pretty close agreement.

During the following months, however, the fraction of transits sighted declined markedly, reaching a low of 10 per cent. To some extent this may have been a seasonal effect because of the difficulties of flying in winter, but the chief reason for the drop was undoubtedly the introduction of search receivers on U-boats which could detect meter-wave radar. This development permitted the U-boats to surface at night with fair safety, and the aircraft available no longer constituted a balanced force. (See Chapter 11 for further discussion.)

During the spring of 1943 the Leigh Light Wellingtons were equipped with centimeter radar and results during the third period were correspondingly improved. By June and July the fraction of transits sighted had *risen* to 100 per cent, a tenfold increase, though the number of flying hours in those months was only about twice what it had been in previous periods. If all the planes had been fitted with centimeter radar, an even higher sighting rate would have been expected on the basis of Table 8, since there was considerably more flying than the 1800 hours per month which should produce 100 per cent sightings. Such was not the case, however, and the average sweep rate of all planes involved was probably more nearly that of meter radar. On this basis 6900 hr per month would be required to produce 100 per cent sightings, which is in good agreement with the observed results. The average amount of flying was 5500 hours per month, which sighted 60 per cent of the transits, reaching a peak of 160 per cent during the best summer months.

It may be concluded, then, that the best periods of the Bay operations provided returns quite in accordance with predictions, but that the U-boats were quick to find and exploit any weak points in the offensive. The highly profitable periods were not of long duration. Even during the low points, however, Biscay operations were quite profitable compared with aircraft patrol in other regions, since the flying hours required to make a sighting rarely rose above 500, whereas in many areas thousands of hours were required.

13.2.2 Value of Interception of Transit Submarines

The final evaluation of any offensive against transit U-boats must be made on the basis of a comparison with other possible uses of the forces involved. When the other use contemplated is also some type of offensive patrol, the chief criterion is that of submarine density (or density of surfaced subs if more appropriate), as is demonstrated in Volume 2B, Chapter 3. Offensive patrol should be carried out in the region of greatest submarine density, subject to certain practical considerations. A region in which weather conditions reduce the effectiveness of detection gear by a factor of three, for instance, would *not* be a profitable one for an offensive unless the submarine density there was at least three times that in other regions.

When the comparison must be made between offensive and defensive operations, many more factors must be considered. The usual objective measure of the effectiveness of antisubmarine operations is the number of ships saved. Defensive operations effect such a saving quite directly, whereas offensive operations have an indirect effect through reduction *in numbers* of submarines operating and through lowering of the morale and state of training of the submarine crews. The latter effect is very hard to assess in any numerical terms. U-boats have usually withdrawn from areas in which their chance of being sunk was greater than about 10 per cent per month of those at sea when there was a safer alternative, but the high sinking rate has often been associated with a low rate of sinking ships, so that the U-boats may have withdrawn in search of more profitable areas, rather than because of any effect on morale. Nevertheless, the U-boats' heavy losses in 1943 were followed by a period of very unaggressive operations, even though the losses suffered were not enough seriously to diminish the size of the U-boat fleet, and there is no doubt that a lowering of morale and experience of crews had something to do with it.

In order to illustrate the type of comparison that must be made, consider a hypothetical situation in which the enemy has a hundred submarines which can spend half their time at sea. He can build five

per month, but we sink the same number by surface craft (*i.e.*, 10 per cent of those at sea each month), so that a sort of equilibrium has been reached. Given, then, a force composed of 40 aircraft, should they be employed either offensively, assuming that each submarine transit would then be sighted in accordance with equations (1) to (3), or defensively for escort of threatened convoys, assuming that the protection offered would be in accordance with the data of Chapter 10?

In each case the number of ships saved by the aircraft must be determined. For the offensive operations the saving can be estimated in the following way:

The immediate effect of the offensive operation is an increased number of submarines sunk per month. This will reduce the number of submarines operating until, in the long run, a new equilibrium is reached. The number of submarines sunk per month will then be equal to the number built. If N is the number of submarines available to the enemy, and T is the length of a submarine patrol in months, then:

$$N = \text{number of submarines at sea, and}$$

$$\frac{N}{T} = \text{number of transits made per month.}$$

The capabilities of the surface craft are assumed to be such that they sink 10 per cent of the subs at sea per month, and data from Chapter 12 show that it is reasonable to assume that about 10 per cent of all aircraft sightings lead to attacks which sink the submarine. Combining these figures with the ability of the aircraft to intercept each transit, we have, at equilibrium:

$$0.10 \times \frac{N}{2} + \frac{0.10N}{T} = \text{No. of subs built per mo} = 5;$$

$$N = \frac{100T}{2+T} \qquad (4)$$

The normal length cruise for a U-boat has been about 2 months. Using this value for T we have $N = 50$ submarines, which is only half the force that was available in the absence of the aircraft offensive. Thus we would expect this offensive use of aircraft to cut the losses of merchant ships in half.

This figure can be compared with the direct defensive value in escort of threatened convoys. The experience quoted in Chapter 10 was that four sorties per day decreased the daily losses by about 65 per cent. If the aircraft force available could provide this extent of convoy coverage, it would be considerably more valuable than when employed offensively, because the 65 per cent figure measures only direct defensive value and does not take into account any attacks on submarines that the planes might make while on convoy escort duty. The total amount of aircraft flying required for the convoy escort would not generally be excessive. During the actual period studied previously there were about 20 convoy-days per month in the "threatened" class, so that only 80 sorties per month would be needed, whereas the aircraft could be expected to fly about 200 sorties monthly. Some threatened convoys may, however, be in positions which cannot readily be covered by aircraft, so that the expected thoroughness of coverage must be estimated on the basis of weather, distance of convoy routes from bases, and similar factors. In the North Atlantic, convoys were, in fact, covered on somewhat less than half the days when they were threatened. If this sort of restriction must be accepted, the expected reduction in losses is only about 30 per cent, which is no longer obviously superior to the offensive employment of aircraft in the transit area. As a matter of fact the sightings made (about 15 per month) were about enough to make up the discrepancy between 30 per cent and 50 per cent saving.

Such a comparison is never strictly valid, however, because it is made on the basis of an equilibrium condition which is not approached very quickly. If we consider N to be a function of time, then equation (4) is replaced by:

$$-\frac{dN}{dt} = 0.10 \times \frac{N}{2} + 0.10\frac{N}{T} - 5 \qquad (5)$$

$$= \left(0.05 + \frac{0.10}{T}\right)N - 5;$$

$$N = N_1 e^{-\left(0.05 + \frac{0.10}{T}\right)t} + \frac{5}{0.05 + \frac{0.10}{T}} \qquad (6)$$

$$= N e^{-\left(0.05 + \frac{0.10}{T}\right)t} + N_{eq}.$$

Here N_{eq} is the equilibrium number of submarines. For the case previously considered, $T = 2$ months, the number of submarines is plotted in Figure 3.

Thus the value of an offensive operation depends

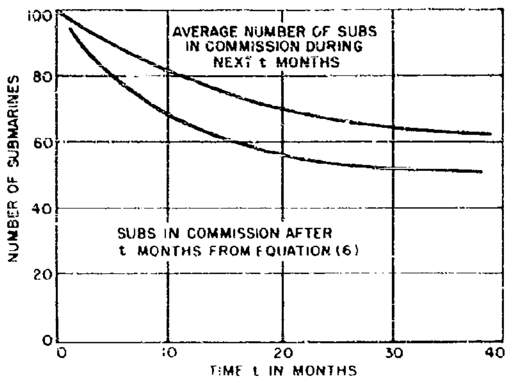


FIGURE 3. Diminution of submarine fleet by an antisubmarine offensive.

on the expected length of the war, the upper curve giving the reduction in the average number of submarines operating as a function of the length of period under consideration. If the war is expected to last another 30 or more months, the offensive will achieve very nearly its equilibrium effectiveness in that the number of submarines operating is reduced by about 40 per cent with the lifetime (and consequently experience) of ships and crews are correspondingly reduced. If, on the other hand, the war is to last only 6 months the average reduction in submarines operating is only about 10 per cent.

The comparison between defensive and offensive measures is made explicitly in Figure 4. The ordinate is proportional to the reduction in ship losses, with no account taken of the attacks on U-boats made by escort aircraft. It is clear that the effect of the length of the war on the value of an antisubmarine offensive and the effect of the probable completeness of convoy escort must be taken into account in arriving at an evaluation of the relative merits of the two possible uses of the aircraft. It is clear also that no general conclusion can be made, but that each decision must be made after a consideration of the tactical and strategical situation obtaining at that time.

13.3 FOLLOW-UP OF CONTACTS

Probably the most important aspect of offensive operations is the attempt to convert the largest possible fraction of all contacts into attacks and kills. Often the manner in which contact is made is such that an immediate attack is not possible. (A typical example would be a sighting by a merchant ship or nonoperational aircraft.) It may be that an attack has been made on the sub and contact subsequently lost, so that contact must be regained in order to continue the attack. In these cases it is usually very profitable to conduct a follow-up search in order to find the sub again.

Follow-up of contacts is a profitable employment of antisubmarine forces because for the first few hours after contact has been lost the region in which the submarine can be is rather small. In this region the probability density is accordingly high and it therefore constitutes a profitable region for search. As an example, consider the case of a submarine whose position is definitely known at time $t = 0$, and is then lost. The submarine is free to travel on the surface. Since its speed is certainly not greater than 20 knots, we can be sure that it is within a circle of radius $20t$ miles. The corresponding submarine probability density is shown in Figure 5, calculated on the assumption that the submarine is equally likely to be anywhere within the circle, that is, that

$$p = \frac{1}{\pi(20t)^2}. \tag{7}$$

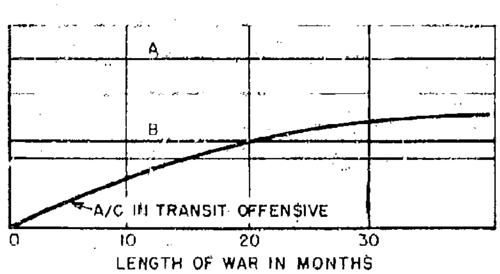


FIGURE 4. Relative saving of ships for various uses of aircraft. (A) Defensive value of escort of all threatened convoys. (B) defensive value of partial escort of threatened convoys.

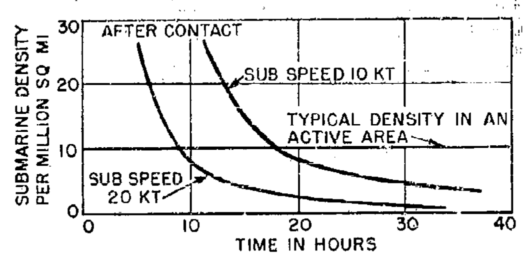


FIGURE 5. Local probability density after a submarine contact; calculated from equation (7).

The horizontal line drawn for comparison shows a typical average U-boat density for an active area during the Atlantic war. The conclusion is that follow-up of the contact is more profitable than general area patrol for about 10-20 hours after the contact, in this case. If the overall submarine density is increased, follow-up of contact becomes relatively less profitable, whereas in a region of low density it is of utmost importance to exploit each contact to the full.

Figure 5, drawn for submarine speeds of 10-20 knots, is applicable for surfaced submarines. If the submarine is held down by aircraft or surface craft, its speed may be considerably less, normally only 2-3 knots for conventional types of submarine. In this case the local density remains high for a much longer period than is shown in Figure 5. Consequently, sonar search for submerged submarines is very much more effective in follow-up of previous contacts than in routine area search. Only in areas of great submarine density is it profitable to employ surface craft for area search by sonar. In general the chief offensive employment of surface craft will be to follow up previous contacts, appropriate plans and tactics for doing so being of prime importance.

There are, then, two distinct tactical situations, according as aircraft or surface craft are the principal agents of search. If the hunt is being carried out by aircraft alone, the aim is to recontact promptly any submarine which dares to show itself on the surface. When surface craft are present, however, the submarine will normally remain submerged. (A coordinated hunt by aircraft should be carried out whenever possible to ensure that the submarine does not make a high speed escape on the surface.) So long as the submarine's submerged speed is low, the surface craft's sonar search has a good chance of resulting in recontact. Of the two problems, that of surface craft search is somewhat the simpler and will be discussed first.

In the actual design of such follow-up searches for surface craft, two primary requirements must be met. In the first place, the search must be as simple as possible to carry out and involve no more turns or changes in disposition than necessary. Ships should be kept in a line-abreast formation unless there is some special reason for doing otherwise. Standardized turns and maneuvers should be employed to avoid confusion in operation. In addition the plan

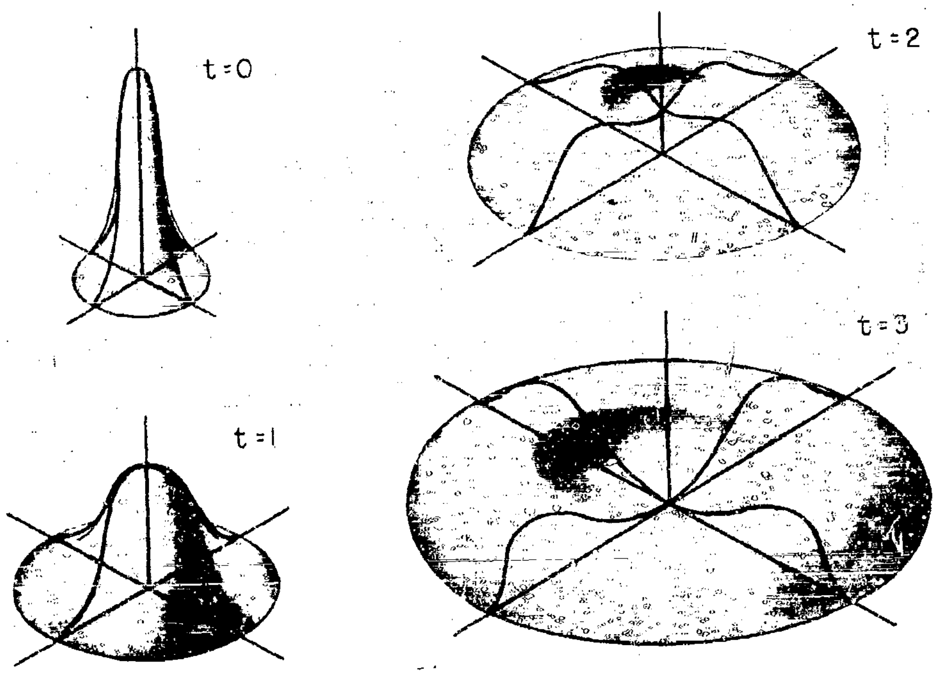


FIGURE 5. Submarine probability as a function of time (t = time in hours).

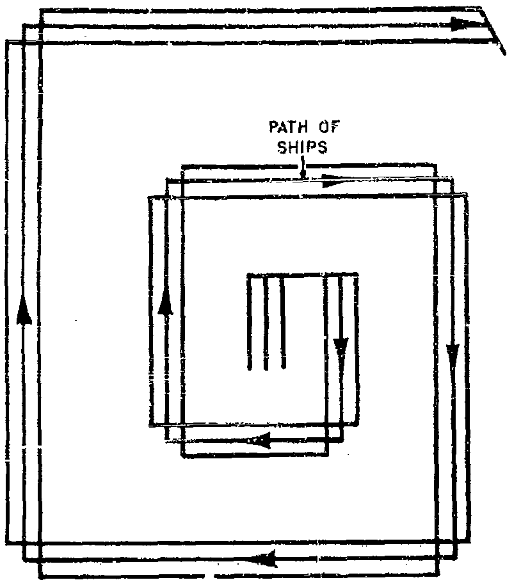


FIGURE 7. Typical plan for sonar search by surface craft.

must search regions in which the submarine is likely to be, in general accordance with the rules of Volume 2B, Chapter 3. In designing the plan, then, an estimate of probability density distribution as a function of time must be made. Immediately after the original contact the density is very highly peaked, the only dispersion arising from errors in reporting the contact position. But as time goes on the submarine may move further and further from the position of the original contact and will probably be at some distance from it. A typical set of densities is shown in Figure 6, and further discussion of such distributions may be found in Volume 2B, Chapter 1.

It is evident that a search plan drawn up on the basis of such an expanding distribution will usually have the general shape shown in Figure 7. Extensive sets of such plans are to be found in present doctrine.[c]

It is not necessary to go through a detailed analysis of probability functions such as those of Figure 6, however, to gain a general idea of the effectiveness of surface craft follow-up tactics. An analysis of the following type is adequate to indicate the importance of the factors considered. The fundamental simplification is to replace the surface shown in Figure 6 by a flat topped cylinder, that is, to assume that the submarine is equally likely to be anywhere within a certain radius of the initial point and is known to be somewhere within that radius. It is reasonable to write the radius as

$$r = \sqrt{a^2 + v^2t^2},$$

where a = uncertainty in initial position,
v = submarine's speed,
t = time since initial contact.

Assume that the increment of probability of having made contact can be written

$$dp = \frac{Q\,dt}{\pi(a^2 + v^2t^2)}(1 - p).$$

This assumption implies that the search is carried out at random, but can be used as a fair approximation to an actual search plan. (See Volume 2B, Chapter 3.) Then

$$p = 1 - \text{const} \times e^{-(Q/\pi a v)\tan^{-1}(vt/a)}. \tag{8}$$

The constant of integration in equation (8) is determined by the condition that $p = 0$ at the time of commencing search. If this time is denoted by t_1,

$$p = 1 - e^{-(Q/\pi a v)[\tan^{-1}(vt/a) - \tan^{-1}(vt_1/a)]}. \tag{9}$$

When a search is being conducted it should normally be carried out until there is nothing to be gained by further searching, i.e., until $p(t)$ is very near $p(\infty)$, which is the ultimate limit. Hence it is useful to write the probability for $t = \infty$, which is

$$p(\infty) = 1 - e^{-(Q/2av)[1 - (2/\pi)\tan^{-1}(vt_1/a)]}. \tag{10}$$

Some typical curves plotted on the basis of equation (10) are plotted in Figure 8. A sweep rate of 30 square miles per hour and a sub speed of 8 knots are assumed. It is evident that a prompt start on the search combined with accurate localization of the contact are required for a good probability of success.

Operational data are available on success of follow-up hunts aimed at regaining contact with a submarine after lost contact following an attack; these can be compared with the theoretical predictions. For

[c] Plans are presented in FTP 223A. The mathematical basis upon which such plans are constructed is given in Volume 2B, Chapters 3 and 7.

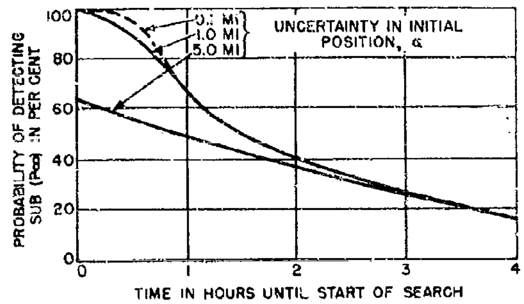


FIGURE 8. Probability of catch for: sweep rate 30 sq miles per hour; sub speed of 3 kt.

cases in which a submarine was believed to be present, the results are presented in Table 10. An average of about two ships took part in the searches.

TABLE 10. Success of searches to recontact U-boat.

No. of cases	Average time from lost contact to start of search	Per cent successful
19	22 min	53
12	90 min	25

These figures are plotted in Figure 9, and a calculated curve is drawn which is in fair agreement with the operational points. This curve is drawn on the assumption that sub speed is 3 knots, initial uncertainty is 1 mile, and sweep rate is 10 sq miles per hour. The first two assumptions are reasonable for the tactical situation involved. Since the problem is one of recontacting a submarine which has been previously attacked, a location error of more than 1 mile is unlikely. The sweep rate of only about 5 sq miles per hour per ship is somewhat smaller than might be expected, however. In Volume 2B, Chapter 6, the average sonar sweep width is estimated at 1800 yd, corresponding to a sweep rate of about 10 to 12 sq miles per hour. Several explanations are possible: (1) in this case U-boats may have been especially careful to make good use of layer effect and other opportunities to escape detection, (2) wakes, depth charge explosions, etc., may have made search more difficult, or (3) the previous estimate, based on the assumption that a submarine would have been detected every time at very short range, may have been unduly optimistic. There is, however, no irreconcilable difference between the theoretical expectations and operational results.

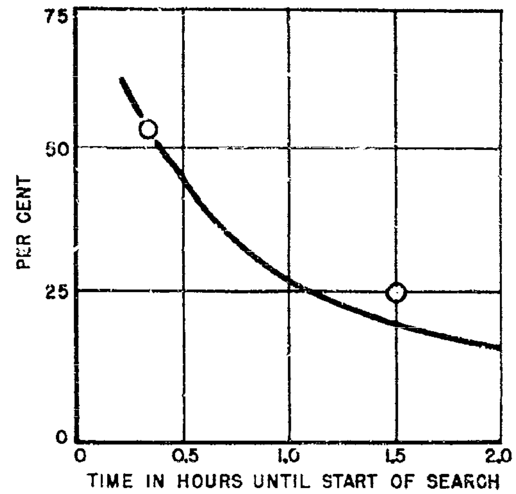


FIGURE 9. Per cent of submarines contacted by surface craft hunts. (Circles are operational data on regaining contact.) (Solid curve is calculated for: $Q = 10$ sq miles per hour, $a = 1$ mile, $U = 3$ kt, by equation (40).)

Follow-up hunts by aircraft are of two general types. The first of these is aimed at detection of submerged submarines by MAD or sono-buoys, the second at visual or radar detection of the submarine when it has resurfaced. Aside from special limitations on maneuverability, those of the first type have much in common with surface craft hunts, since the submarine's behavior is approximately the same. In order to have an acceptable chance of success the search must be begun very soon after the initial lost contact, and the accuracy of locating the initial point must be high. Since this type of follow-up presents no essentially new problems, detailed discussion will not be given here.

When, however, the aircraft relies on visual or radar detection, the search must be planned with recognition of the fact that a submerged submarine cannot be detected. Two alternatives are possible: either a hold-down hunt aimed at covering all possible positions of the submarine so as to keep it from surfacing until battery and/or crew endurance are exhausted, or a "gambit" procedure in which the aircraft endeavor to permit the submarine to resurface and then recontact it. This latter alternative is equivalent to designing the search so as to concentrate on those regions in which *surfaced* submarines are most likely to be. In practice the gambit procedure has usually involved a box search centered at

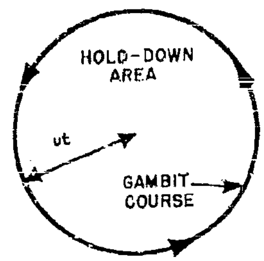


Figure 10. Comparison of follow-up hunts.

the point of last contact and far enough distant that the sub will surface and then try to cross the aircraft's patrol. The hold-down hunt, on the other hand, must cover the whole possible area of the submarine at frequent intervals. This requires a much larger expenditure of effort, actually far more than is usually available, as can be seen in Figure 10.

Hold down	Gambit
1. Aircraft must cover area πu^2t^2 about 3 times per hour so as to keep sub down at all times.	1. Aircraft must make circuit $2\pi ut$ in length often enough to prevent crossing on surface.
2. For velocity of aircraft = V, and sweep width = W, this requires $3\pi u^2t^2/WV$ aircraft in the region at time = t.	2. For aircraft velocity = V, sweep width = W, and sub surfaced speed U, this requires $(U/W)(2\pi ut/V)$ aircraft flying at time = t.

3. To carry out from 1 hr to 36 hr with $u = 3$ kt, $W = 10$ miles, $V = 125$ kt, and $U = 15$ kt we require:

Hold down	Gambit
1050 flying hours	150 flying hours

Obviously much less flying is required for the gambit procedure than for hold down, especially since a true hold down should last for well over 36 hr. As a matter of fact, there have been very few cases where hunts have been made with sufficient intensity to qualify as true hold-downs offering the submarine *no* opportunity for surfacing. A hard and fast distinction cannot be made in the case of actual operations.

Operational results normally confirm the theoretical expectation that flying on hunts in follow-up of contact is more profitable than any other type in terms of flying hours required per submarine contact. Table 11 presents data of this sort from the Trinidad Area for the period August 1942 to January 1943. Hunt flying is seen to be three to four times as profitable as other types.

Table 11. Hours of flying on contact by type of mission (Trinidad area).

	Total hours of flying			Avg hours per contact		
	Escort of convoy	Routine patrol	Hunts	Escort of convoy	Routine patrol	Hunts
Aug 1942	711	1,514	131	711	116	45
Sept	1,085	3,405	186	362	227	97
Oct	189	3,852	701	163	241	88
Nov	925	3,221	584	[illegible]	103	584
Dec	658	3,171	620	319	3,171	124
Jan 1943	1,038	2,668	186	519	1,834	234
Total	4,889	18,831	3,014	444	342	125

A small number of aircraft hunts have been studied in detail in order to determine the relative effectiveness of different types of follow-up tactics. Although the number of cases involved was too small to permit great reliance to be placed on the results, they are of interest as confirmation of the expected trends. A total of 18 hunts are involved, which occurred between March 15, 1943, and October 20, 1943, in the United States Strategic Area. The overall results are summarized in Table 12.

Table 12. Results of aircraft hunts. (United States strategic area, 1943.)

Total number of hunts	18
Hunts achieving recontacts	11
Per cent of hunts successful	61
Average duration of hunt (hours)	59
Total number of recontacts made	22
Recontacts per hunt	1.22
Average time between recontacts (hours)	14.6

The effectiveness of these hunts is shown by the fact that 61 per cent of them succeeded in again establishing contact with the submarine. On the average, subs were recontacted about two times in those cases. A more detailed breakdown of the results is presented in Table 13.

Table 13. Comparison of results by hunt type.

	Continuous gambit	Modified exhaustion	Exhaustion
Number of hunts	12	2	4
Number successful	9	1	1
Per cent successful	75	50	25
Average flying hours in hunt area	75	280	300
Number of recontacts per hunt	1.33	2.50	0.25
Flying hours in area per recontact	58	114	1,186

This table shows clearly the high effectiveness of the gambit type of hunt in comparison with other types. It ranks well in terms of percentage success an average number of recontacts per hunt. Since the number of flying hours employed was much smaller than for the other types, the results in terms of flying hours required per recontact show a definite advantage to the gambit type.

In connection with the general importance of follow-up hunts, one further remark is worth while. Such hunts are profitable because they are carried out in a small area in which the submarine probability density is high. For best effectiveness accurate navigation is required to locate the area properly and to carry out the desired search plan. in addition communications must be excellent in order to assure that the hunting craft reach the submarine position at the earliest possible moment, since the early stages of the hunt are the most profitable. In order to insure that coordinated follow-up hunts are carried out successfully, great skill is required in each of these fields.

Chapter 14

EMPLOYMENT OF SEARCH RADAR IN RELATION TO ENEMY COUNTERMEASURES

14.1 INTRODUCTION

RADAR has been only one of the many weapons applied to defeat the German use of U-boats, but it has played an important role at certain critical times. Because the U-boat high command failed to anticipate the effectiveness of search radar, its use by the Allies caused especially grave concern to the U-boats. The moves and countermoves of the radar war offer an interesting example of the importance of quick and accurate evaluation of enemy measures. Although the events of World War II conform in general to the scheme of measures and countermeasure set forth in Volume 1 on Operations Research, a review of them shows that evaluation of the operational effectiveness of enemy countermeasures is of utmost importance. Even when a countermeasure has excellent theoretical performance, it is a rare event for it to be applied widely enough and with sufficient operational effectiveness to justify the extreme tactic of abandoning the weapon being countered. Usually the prompt (but not premature) application of counter countermeasures will largely restore the effectiveness of the weapon. This has been particularly true of the radar versus search receiver competition which arose during the latter part of the U-boat war.

The following discussion will accordingly pay primary attention to the development of German search receivers and the counter countermeasures employed to reduce the effectiveness of the German gear. In addition, the importance of Schnorchel and radar camouflage as a countermeasure to Allied search radar will be considered. There have also, however, been a number of less important German radar countermeasure developments, which are described briefly below.

1. *Submergence.* It is evident that the submarine can escape radar detection by staying submerged, and in the final phases of World War II German U-boats made a policy of keeping below the surface as much as possible when in dangerous waters. As pointed out in previous chapters, however, the loss in mobility and in offensive capabilities was very serious, and a normal type of U-boat (without Schnorchel) could not operate effectively using maximum submergence tactics. Such tactics as these must be considered a very unsatisfactory last resort from the submarine's point of view.[a]

2. *Aircraft warning radar.* Radar of this type (Hohentwiel) was developed and installed on a considerable number of U-boats. Its use was slight, however, and successes insignificant. This was due to two factors, the relatively low power and short range of this radar and the fear of Allied search receivers. In general the range on aircraft of the long-wave, low-power U-boat radar was shorter than the range on surfaced U-boats of Allied microwave air-to-surface-vessel [ASV] radar. This increased the lack of confidence in radar current among U-boat commanders which was caused by their basic objection to any radiation of energy which could be listened to and located by direction-finding devices. They were convinced of the danger of Allied listening gear long before it existed in adequate quantity to be of operational importance. This threat was sufficient to nullify the use of U-boat radar. This fact has been subsequently established from statements made by German personnel but was appreciated earlier on the basis of information obtained from ferret planes equipped with listening gear. They were dispatched to areas in which U-boats were known to be operating, but the sequence of negative reports showed that there was no significant use of the radar sets installed on the U-boats. Meanwhile laboratory developments and small-scale production of homing and direction-finding search receivers anticipated a revival of U-boat radar. It is possible that submarine radar would

[a] At the end of the war German U-boats of high submerged speed (10-15 knots for Type XXI, 15-25 knots for the proposed Type XXVI) were approaching operational status. They were designed to operate effectively when submerged and would have been able to stay submerged using Schnorchel to escape radar detection, yet retain potent offensive capabilities because of their special propulsion for high submerged speed. Conclusions drawn from operations involving old-style U-boats may be completely inapplicable to these new types. Their development shows, however, that the Germans had realized that the other types were not satisfactory for completely submerged operation.

be a handicap rather than a help if opposed by adequate airborne listening gear.[b]

3. *Radar decoy.* Various types of radar decoys or false targets have been employed in the hopes of drawing the attention of Allied radar search craft away from the U-boats themselves. Metallized fabric-covered balloons [RDB] and arrays of reasonant dipoles on spar buoys (Thetis) have been used, especially in the Bay of Biscay. In sufficient numbers they might be expected to lead to a serious waste of search time and effort and there has been at least one instance of a United States surface vessel being torpedoed while investigating a decoy target. In general, however, decoys have not been very successful in confusing Allied ASV radar search, largely because they proved to be too small as radar targets to be detected. In addition, careful study of target motion aids the radar operator in distinguishing stationary spar buoys or wind blown balloons from true targets.

The most significant German countermeasures to Allied search radar have been twofold: first, the development of intercept receivers and, second, the development of Schnorchel and associated radar camouflage. These will now be discussed.

14.2 THE PROBLEM OF GERMAN SEARCH RECEIVERS

For submarines, in particular, employment of an effective radar intercept receiver provides a very satisfactory countermeasure to search radar. Upon receiving a signal of sufficient intensity from the enemy radar, the submarine can dive and become completely hidden. So long as the intercept receiver can be depended on to outrange the enemy radar (as it should, in principle, usually be able to do), the protection offered is complete. Nevertheless, such complete protection is rarely achieved in practice. (See Chapter 5 in Volume 2B.) It is valuable to describe the various stages in the radar versus search receiver competition that took place in the U-boat war as an example of the problems involved in evaluating correctly the effectiveness of countermeasures of this type.

14.2.1 Meter Radar Is Compromised by Metox German Search Receiver

Even as early as August 1941 it had been suggested, since aircraft not employing ASV radar were more successful than aircraft using ASV in sighting U-boats, that U-boats were detecting ASV transmissions. To obtain evidence of this an experiment was carried out by Coastal Command, and aircraft operating off Brest observed ASV silence on alternate weeks for a brief period. The results of this experiment, given in Table 1, showed that there was no evidence of any disadvantage involved in the use of ASV, since aircraft using radar made more contacts than those not using radar in the same amount of flying.

TABLE 1. Contacts with and without radar. (Biscay area, September 1941.)

	Radar off	Radar on
Flying hours in area	528	541
Contacts: Visual	3	$5\frac{1}{2}$
Radar	...	$2\frac{1}{2}$
Total	3	8

Later intelligence showed that this conclusion was indeed correct. From the start of World War II, the Germans were fully aware of the possibilities of meter ASV radar and had developed their own airborne search equipment, but it was not until the summer of 1942 that they concluded that the Allies were using radar for U-boat search and initiated a hurried program for the development of search receivers to detect the radiations. The first equipment to be installed on U-boats was the R-600 or Metox with a low wavelength limit of 130 cm. It was of the heterodyne type, thought to be the only type capable of sufficient sensitivity, and so it radiated energy, a property which eventually caused its abandonment. Nevertheless, it was used with apparent success, and the conditions of its introduction and use are of considerable interest.

[b] United States submarine crews have to some extent shared the Germans' suspicion of aircraft warning radar and convinced themselves that the Japanese were homing on SD radar transmissions from a number of individual incidents which seemed to indicate such homing. Many of them ceased to use SD radar. Statistical data showed, however, that no effective homing was taking place as late as December 1944, as can be deduced from the table below.

	Aircraft contacts per 100 days (in Luzon strait)		Percentage of aircraft (all areas) that detected subs	
	Day	Night	Day	Night
SD nonusers	84	23	12	10
SD users	86	21	9	8

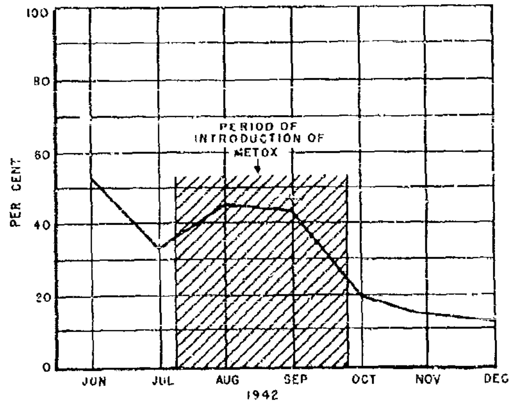


Figure 1. Fraction of U-boat transits of Bay of Biscay that were sighted.

The German development of search receivers was closely related to the progress of the aircraft anti-U-boat offensive in the Bay of Biscay. In June 1942 the introduction of night attacks by Leigh Light Wellingtons and the accompanying sharp rise in the number of attacks made on U-boats caused the Germans to take some action, and the Metox German search receiver [GSR] was the result. Its operational success against the British Mk II radar was considerable, as sightings in the Bay transit area were greatly reduced. Figure 1 shows that the fraction of U-boat transits sighted dropped markedly with the introduction of Metox after the summer of 1942, although the amount of flying done remained approximately constant.

During the period shown in Figure 1 data on the effectiveness of radar search were also obtained in other regions than the Bay of Biscay, for example, in the Trinidad area of the Caribbean Sea Frontier.

Table 2. Contacts with and without radar (Trinidad area, Aug 1942–Jan 1943).

	Hours of flying		Contacts		Effective search rate in sq miles per hour	
Month	No radar	Radar	No radar	Radar	No radar	Radar
Aug	1,511	851	11	6	526	507
Sept	3,326	1,650	8	15	93	354
Oct	1,878	2,464	6	21	120	218
Nov	1,016	3,714	0	9	0	119
Dec	3,229	1,200	0	2	106	95
Jan	3,648	1,544	1	2	97	111
Total	14,608	12,123	35	55	127	241

These data, like those obtained earlier by Coastal Command, showed little evidence of any effective use of radar listening gear by the U-boats, as shown in Table 2. Two conclusions were possible, either that the use of the gear was much less effective in the Trinidad area than the Bay of Biscay or that the change in the Bay was not due to Metox but was, for example, a seasonal change. The actual situation may have involved more psychological benefit from the Metox than physical benefit. The use of Leigh Light Wellingtons in the summer of 1942 may have scared U-boats into abandoning the policy of surfacing at night even though the number of planes was small and surfacing in the daytime was still much more dangerous. With the advent of Metox they may have returned to the safer policy of nighttime surfacing. In the Trinidad area, on the other hand, there was no radical change in U-boat tactics except for a general increase in caution.

If this last explanation is taken as the correct one it is still, in a sense, fair to say that Metox caused the change in Bay of Biscay results in the fall of 1942. It would not be safe, however, to conclude that Metox was, therefore, a very effective search receiver. The actual mechanism linking cause and effect was a more subtle one. Whatever the explanation of the apparent success of Metox, it was short-lived, for the Allies soon introduced S-band (10 cm) radar and the effectiveness of air search reached even higher levels than before.

16.2.2 Germans Baffled by S-Band Radar

Meanwhile, Allied development of airborne S-band radar was proceeding, based on the magnetron transmitter tube, and it was put into operational service early in 1943 as the U.S. SCR 717 and ASG, and the British Mk III types. This new wave band not only provided immunity from detection by Metox but also gave increased ranges of detection on U-boats.[a] The operational success of this type of gear was considerable. Aided by the seasonal upswing in aircraft effectiveness normally occurring in the spring months because of better weather and more daylight hours, S-band radar had much to do with the peak of aircraft achievements reached in the summer of 1943.

Evidences of the success of the air war against

[a] See Volume 2B, Chapter 5, for detailed discussion of radar ranges.

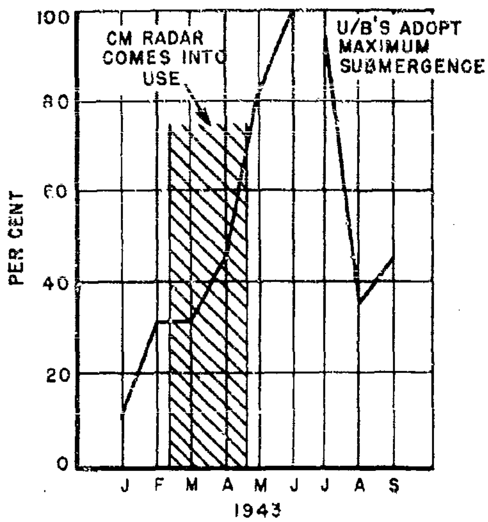


FIGURE 2. Fraction of U-boat transits of Bay of Biscay sighted.

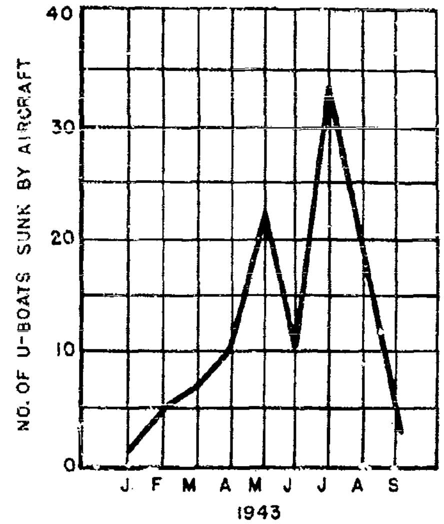


FIGURE 3. U-boats sunk per month by aircraft.

U-boats at that time are shown in Figures 2 and 3 below. Figure 2 presents data on the sighting of U-boats passing through the Bay of Biscay. The sharp rise in the spring months is very evident. In Figure 3, which gives the overall results of the aircraft offensive in terms of U-boats sunk per month, there is also a sharp rise at this time. S-band radar was by no means the only cause of this increase in air effectiveness, but there is no doubt that it made a significant contribution. The other major factor was the introduction of aircraft based on escort carriers for mid-ocean offensive operations.

With this upswing in Allied aircraft success, the Germans became convinced that Allied aircraft were using some new detection device and started a frantic activity to identify and counter it. For a time they occupied themselves with the idea that it was an infrared detector, since they had tried to develop one of their own, and experimented with special paints intended to give no infrared reflections. They also considered the possibility of a frequency scanning radar and developed a scanning receiver with a cathode-ray tube presentation. This was of definite advantage to the operator, but it still covered only the same meter-wave band. The sinkings of U-boats continued.

In desperation they jumped to the conclusion that their GSR radiations were being homed on. The Metox receiver was outlawed and the Wanz G-1 introduced. This was of an improved design and radiated much less power. However, the almost pathological fear of radiation which had been bred in the minds of U-boat captains prevented them from trusting it. Continued sinkings and skepticism of the technical advantages kept it from being used.

Next the German scientists turned to the much less sensitive crystal detector-receiver, which was entirely free from radiation, and produced the "Borkum." This was a broad-band intercept receiver which covered the 7-300 cm band. Neither it nor the Wanz was effective against the new Allied radar, however.

Finally, in September 1943, the U-boat command realized that 10-cm radar was being used against them. The "Rotterdam Gerat," a British H_2S radar working in the 10-cm band, had been captured intact at Rotterdam by the German Air Force in March 1943, and German scientists had soon determined its characteristics. How the 6-month delay from March to September occurred is unexplained. It was a significant time factor in the U-boat war. A further delay of about 6 months intervened before the first really effective S-band receivers became operational in April 1944. During this interval the frantic experimentings of the German Technical Service became evident in such incidents as the patrol of the U-406 carrying one of their best GSR experts, Dr. Greven, and his staff, with a full complement of experimental

search receivers. The U-406 was sunk, and other experimental patrols also had short careers.

The drop in results of the Allied air effort at the end of the summer of 1943, which is shown in both Figure 2 and Figure 3, was only in small part due to GSR developments. The U-boats simply adopted an ultraconservative policy of maximum submergence and rarely exposed themselves to air attack. In passing through the Bay of Biscay they crept along the Spanish coast, in regions inaccessible from Britain, and surfaced as little as they could. With such tactics U-boat effectiveness was very low, but they gained respite from air attack.

14.2.3 Naxos Search Receiver Covers S-Band

Out of this confusion finally came the "Naxos" intercept receiver covering the 8–12 cm band. The first models introduced in the fall of 1943 were crude portable units mounted on a stick and carried up through the conning tower upon surfacing. The range was short, because of the crystal detector principle, the broad band coverage, and the small, nondirectional antenna; estimates of range from prisoner of war reports were 8 to 10 miles.

Allied reaction to intelligence reports about Naxos as early as December 1943 brought the fear that S-band radar was compromised. Even earlier than this (November 1942) "disappearing contacts" had led many to assume compromise long before 10-cm search receivers were thought of by the Germans. A serious morale problem developed among Allied ASV flyers with this news and the drop in U-boat contacts. Radar was turned off completely in several squadrons where its use could only have resulted in more numerous contacts. Tactics were improvised to salvage some usefulness for the radars on the assumption that the GSR would outrange the radar (an assumption that was largely false). Some of them are listed below.

1. Prohibition of special radar procedure during the approach, such as "searchlighting" the target, sector scan, or change of scan rate, since such changes would indicate to a GSR operator that radar contact had been made, and the U-boat could then take evasive action. (It was considered unlikely that U-boats would dive immediately on receiving a signal on GSR.)

2. Attenuators, such as "Vixen," were initiated to cause a slow and steady decrease in transmitted power as range closed and so to confuse the GSR operator. In order to use Vixen successfully, the contact must be made at a range of 15 miles or greater and the cycle started soon after. Since this is greater than the average radar range under many conditions, it could only be used for less than half the contacts. Production was slow and installation slower, with the result that Vixen had no operational opportunity for justifying the effort spent in its development.

3. An interim tactic of "tilt-beam" approach was proposed to reduce signal intensity as range was closed by tilting the radar beam up off the target. This requires unusual skill and cooperation between pilot and radar operator to be effective, and its value has never been adequately proved.

4. Almost in desperation the tactic of turning the spinner aft (for the 360-degree scanning radars) and approaching by dead reckoning was suggested. The chances of a successful navigational approach are small, however, as compared with radar homing on the target, and this proposal was not very promising.

A serious error in some Allied thinking at this phase consisted of overestimating the capabilities and efficiency of the Naxos GSR. It was felt that such a search receiver would completely nullify the effectiveness of S-band radar, but such did not prove to be the case. The data presented in Table 3 show the effectiveness of night flying during the period October 1943 to January 1944 in the Bay of Biscay (the region in which use of GSR might be expected to cause the largest reductions).

If we consider that the discrepancy between expectation and results obtained is entirely due to

TABLE 3. Results of S-band radar night flying. (Bay of Biscay, October 1943–January 1944.)

Type of aircraft and radar	Expected contacts on basis of previous months	Sightings	Disappearing contacts probably on U-boats
Wellingtons, British Mk III	62	15	23
Halifaxes, British Mk III	32	18	15
Liberators, ASG, searchlights	30	12	14
Liberators ASG no searchlights	25	1*	13
Total	149	46	65

* This poor showing probably due to lack of experience.

GSR, we would conclude that it enabled 25 per cent of the U-boats that would normally have been contacted to escape detection altogether, 44 per cent to dive after being contacted by radar but before being sighted visually, leaving 31 per cent that were still sighted, even with GSR. At the most, then, it can be concluded that a reduction of 69 per cent was caused. As an overall average, day and night, including other areas, the reduction would be much less, possibly 25 to 50 per cent. Since the sweep rate in S-band radar search is under most conditions several times that for visual, the use of radar was still imperative.

Efforts were made, therefore, to revive the confidence in radar and keep it in operation. Contacts by S-band radar continued to be made, and it became evident that the Germans did not have much confidence in the effectiveness of their search receivers, nor did they use them consistently. In the coming months they were to become more and more committed to the use of Schnorchel rather than search receivers to defeat Allied radar.

11.2.4 X-Band Radar and Tunis GSR

Since an S-band search receiver could, in principle, be highly effective, the use of radar of an even higher frequency was an obvious next step as a countermeasure to Naxos. Development and allocations of X-band (3 cm) equipments even preceded the advent of Naxos and were further stimulated by the problem it presented. However, the Germans were not caught napping this time. An H$_2$X blind bombing aircraft was lost over Berlin in January 1944, and from the damaged remains the Germans learned of the new frequency band. It was assumed that this frequency would also be applied to ASV radar, and the development of X-band intercept receivers was started before use of the X-band radar by the Allies in U-boat search had produced many results. A well designed receiver was developed, known as Tunis, which consisted of two antennas, the Mucke horn for X band, and the Cuba Ia (Fliege) dipole and parabolic reflector for S-band, and installations started in the late spring of 1944. Installations seem to have been completed during the period of inactivity following the withdrawal to Norwegian and German bases, but the operational use of Tunis was not great, because of the reliance placed on Schnorchel from that time on.

The chief feature of Tunis was the directional antennas which gave increased sensitivity and range. To obtain full coverage, the antennas were rotated manually at about 2 rpm. Allied tests on captured specimens of this gear showed good performance with a range of about 15 miles on an aircraft at 100 ft increasing to 40 miles or more at altitudes in excess of 1000 ft. Ranges obtained in operational use were undoubtedly somewhat shorter, but Tunis was apparently an effective search receiver.

The outstanding tactic proposed for Allied use against Tunis was intermittent radar operation. A schedule of two or three radar scans at intervals of 1 to 2 minutes for a narrow-beam radar will point the beam on target for only a small fraction of the time. Since the sweeping GSR beam is only occasionally pointed at the aircraft, and since a coincidence of these events is necessary for the GSR to achieve a detection, the probability of detection by GSR can be made rather small. Discussion of this procedure is given in Volume 2B, Chapter 5. Since it was not used to a significant extent in operations, it will not be discussed further here.

11.3 USE OF SCHNORCHEL AND CAMOUFLAGE

Apparently dissatisfied with search receivers as a means of achieving immunity from radar detection, the U-boat Command turned to more drastic measures during the last year of the war. The development of Schnorchel was carried out during the latter months of 1943 and fitting of the equipment to U-boats began early in 1944. Using Schnorchel for Diesel intake and exhaust, the U-boat could run at periscope depth with only a small Schnorchel head showing above the surface, yet accomplish the ventilation of the boat and recharge of batteries that previously had required surfaced operations. Starting in the spring of 1944, U-boats spent very little time on the surface, employing Schnorchel or electric propulsion almost exclusively.

Original Schnorchel gave reduced radar echoes merely because of their small size. As a result the average range of detection is reduced to about a third of that on a surfaced U-boat. In addition, the echo is frequently too small for detection until it has entered the area of sea returns which mask it quite effectively, and many potential Schnorchel contacts are missed completely for this reason. Even without camouflage, a Schnorchel is a difficult target to detect by radar. Not content with this state of affairs,

the Germans developed nonreflective coatings for application to Schnorchel which still further reduced the echo from it. Fortunately this camouflage reached operational use only a few months before the end of World War II.

14.3.1 Radar Detection of Schnorchel

In order to evaluate the performance of radar in detecting Schnorchel numerous trials have been conducted with dummy or mockup Schnorchel targets. It is not intended to present a summary of them here. The values quoted in Table 1 are typical. The figures

TABLE 1. Test results on Schnorchel detection. (ASWDU trials.)

	Type radar	
	AN/APS-15	ASG
Average range on surfaced sub (miles)	32	19
Average range on Schnorchel (miles)	10.5	11
% runs on which contact made on Schnorchel		
Sea states 1 and 2	82	67
Sea states 3 and 4	55	32

show a serious reduction in both range and reliability of detection as compared with that on a surfaced U-boat. Depending on the radar set involved and the sea state, the reduction in sweep rate varies from 75 per cent to 95 per cent, even though the position of the Schnorchel was approximately known in these trials, which would make detection unrealistically easy.

Operational results have been even more discouraging. For the period November 1944 to March 1945 an analysis was made of a region near the British Isles which contained about 0.25 U-boat per 1000 sq miles. Assuming that they had been Schnorcheling about a quarter of the time, the expected number of sightings made by the 19,360 flying hours done in the area would be

$$\text{Number of sightings} = \text{area swept} \times \text{density of Schnorchels}$$

$$= 19{,}360 \times Q \times \frac{\frac{1}{4} \times 0.25}{1{,}000}$$

$$= 1.2Q.$$

The total number of sightings and disappearing radar contacts made at night was 16, so that

$$Q = \frac{16}{1.2} = 13 \text{ sq miles per hour.} \tag{1}$$

The sweep width is then about 1/10 of a mile, only about 1 per cent of the value on a surfaced U-boat. In operations, therefore, Schnorchel has been very successful in countering radar detection. In the daytime, when visual sightings are also possible, its immunity from contact is not quite so great. The sweep width has been estimated at 0.6 mile.

14.3.2 Countermeasures to Schnorchel

A number of countermeasures to Schnorchel have been employed, among them the following.

1. Modifications in tactical doctrine to match the decreased radar sweep width (see Volume 2B). This is not a universal scale factor, but must be analyzed for each search plan. For example, the shorter aircraft radar range is partially compensated for by the decreased submarine speed.
2. Radar modifications to improve the efficiency of contact, such as sea return discriminator circuits.
3. New radar developments of high-power, narrow-beam, short-pulse equipments designed to provide better resolution in search for small targets.

These have, however, by no means solved the problem, and Schnorchel remains a very difficult object to detect. In the overall picture of ASW, surface craft have played a very important part in combatting Schnorchel operations. The decreased speed and mobility of a Schnorcheling submarine require it to operate in relatively restricted waters and local areas. In such conditions search and counteroffensive operations by surface craft have good chances of success. As mentioned in Chapter 13, the use of sono-buoys for detection of Schnorchel has promise.

14.3.3 German Camouflage Developments

The general problem of radar camouflage had been under intensive study in Germany since June 1943, but the decision to apply absorptive coatings to Schnorchels was not made until the fall of 1944. Plans were made and put into effect at this time to provide microwave protection for all U-boats, and it is estimated that 100 to 150 craft were actually fitted with coated Schnorchels before the end of March 1945.

Two types of coatings were employed, the Jaumann and Wesch absorbers. The Jaumann absorber was made up of spaced graduated layers of semicon-

ducting paper. The Wesch absorber was made up of rubber mat containing a high percentage of iron powder.

The Jaumann absorber was the more effective, and German reports appear to be reliable in that the range of detection on a Schnorchel coated with it was only 15 per cent of the range on the uncoated Schnorchel. One of its disadvantages, however, was that it had to be preformed and could be used only on flat and cylindrical surfaces. The absorptive properties of the Wesch absorber were not so good.

It may be concluded, therefore, that the use of such absorbers would make Schnorchel practically safe from detection by 10 cm (and also 3 cm) radar. The Germans were concerned with the possibility of danger from radar of longer wavelengths, but it is doubtful that radar of this type would be very effective against such small targets. Use of a variety of frequencies would counter the effectiveness of these absorbers to some extent, until absorbers are developed to cover the whole microwave band.

14.4 CONCLUSIONS

It can thus be seen that this succession of measures and countermeasures, tactical and otherwise, represented, in the main, a series of concessions by the U-boats to the effectiveness of radar-equipped aircraft. The result has been a great reduction in the mobility and attack potential of the U-boats, which, however, has gained them considerable immunity from airborne radar search. This situation was recognized very clearly by the Germans, and their large-scale program for the development and introduction of new types of U-boats of increased underwater speed and endurance was an attempt to overcome these limitations. Whether future submarines, which will probably be forced to operate almost totally submerged (or on a Schnorchel), can achieve the success which submarines had in World War II is a problem for speculative analysis beyond the scope of this discussion. New technical developments make it seem quite possible, however.

Chapter 15

COUNTERMEASURES TO THE GERMAN ACOUSTIC TORPEDO

15.1 INTRODUCTION

During the last 20 months of World War II German U-boats made operational use of acoustic torpedoes, which were first employed in September 1943. The general performance of the torpedo is as follows: It is fired in the normal manner, that is, under gyro control on a collision course. When the torpedo comes sufficiently close to a noise source, such as the ship's propellers, it hears the noise and "homes" on it, *i.e.*, turns towards the source and attempts to keep headed towards it until a hit occurs. The torpedo need merely come within homing range of the ship to have a high probability of hitting. In effect it makes for itself a larger and more circular target than that of an ordinary "straight-run" torpedo. The louder the ship (in the frequency band received by the torpedo), the greater will be the homing range and consequently the effectiveness of the weapon.

15.1.1 Types of Countermeasures

The simplest of the several possible countermeasures to such a torpedo, slowing the target, is suggested by the fact that a ship's sound output increases rapidly with speed. A ship is so much quieter at 7 knots than at 15 knots that the homing range is only about one fifth that at the higher speed, and the effective target size is correspondingly reduced. Slowing considerably increases vulnerability to torpedoes of other types, however. Other means of quieting the ship's propellers, such as masking them with bubbles, have at best halved the homing range in tests to date.

Slowing the ship is an example of a *tactical* countermeasure since no new gear is required for its introduction. A *matériel* countermeasure, on the other hand, is one which does involve the use of special equipment. Another type of tactical countermeasure is possible if the target ship has sufficient warning as to when and where the torpedo is fired and if the torpedo's homing range is not too great. A radical maneuver may be made which will keep the ship out of listening range of the torpedo. This has been called a "step aside" when used by an antisubmarine vessel attempting to approach the submarine for an attack. It is useful only when contact has been made at long range and hampers the ship considerably in its attempt to get in to sonar contact.

The third tactical countermeasure is to maintain a speed greater than that of the torpedo and is therefore unavailable to many ships. A torpedo homing on a target faster than itself will usually be left behind. Its listening sensitivity is limited by its own self noise,[a] which in turn increases rapidly with its speed. Thus some compromise is required between speed and homing range, and an acoustic torpedo will usually be slower than its straight-running counterpart. The ship speed required to outrun the German torpedo was initially considered to be about 20 knots; this estimate was later raised to 25 knots, but final information indicated that 20 knots was adequate after all. Continual rumors of a 30-knot modification of the torpedo cast doubts on these figures, however.

In addition to the above tactical countermeasures, there are several possible matériel countermeasures. These usually involve *noisemakers* [NM's], which are small devices, yet several times louder than a ship at the frequencies *received* by the torpedo. The NM's must be placed so as to attract the torpedo on its initial approach and thereafter prevent its getting into a position to home on the ship. By the end of 1943 escort vessels were equipped to tow one or two noisemakers about 200 yd astern. Equipment of this type was the standard matériel countermeasure employed during the remainder of World War II.

The evaluation of such countermeasures would be much simplified and shipboard morale much improved if some indication were given when a torpedo has been successfully countered. Development work was done on several devices to detonate the torpedo before it reached the ship. These included nets, rotating barriers, explosive streamers, and magnetic fields set up by trailing electric cables. They

[a] Noise generated by the torpedo itself, particularly its propellers, makes a substantial contribution to the background noise heard by the acoustic mechanism. This contribution is called self noise.

were simplest and most effective when used with towed NM's. However, they were never issued because they were fragile, difficult to handle, uncertain in effectiveness, and seriously impeded the ship's maneuvering.

A towed NM alone interferes considerably with the antisubmarine vessel's offensive. The towline restricts the maneuverability of the ship, and the sound generated interferes with sonar and gives the submarine early hydrophone warning. To get around these disadvantages consideration was given to expendable noisemakers projected from the ship or dropped astern. By 1945 such noisemakers had been produced for masking U. S. submarines from enemy sound gear, and their practicability as a torpedo countermeasure had been tested. As long as there is danger of a torpedo being fired, an NM must be projected at least once every 90 sec. This expenditure is feasible only when a submarine is known to be close. It has long been envisaged that the ultimate countermeasure to acoustic torpedoes would incorporate a detector which would give sufficient warning of an approaching torpedo to investigate the successful use of expendable NM's. Such a detector is not yet available.

15.1.2 Scope of Further Discussion

The bulk of this chapter deals with the evaluation of towed NM's, since this type of countermeasure was of primary importance during World War II. The effectiveness of such a countermeasure depends on the mode of operation of the torpedo, and, therefore, the discussion deals chronologically with the evaluation in the light of changing information concerning the nature of the torpedo.

The most important information to be gleaned from operational data is also included. The data are discouraging since in most cases only those torpedoes which hit ships are detected. In addition it is difficult to decide which torpedoes were acoustically controlled and this makes interpretation of the data uncertain. It is hoped that these difficulties can eventually be overcome by analysis of German Admiralty records, which should give further information on the operational effectiveness of Allied noisemakers.

Expendable NM's did not see operational use and will not be discussed further. They must be kept in mind, however, as having possible future usefulness.

Detailed evaluation of tactical countermeasures is also omitted. It is now felt that high speed is the only tactical countermeasure likely to be very effective, and it can rarely be used.

15.2 DEVELOPMENT OF TOWED NOISEMAKERS

15.2.1 German Introduction of Acoustic Torpedoes

By early 1943 intelligence information indicated that the Germans had an acoustic torpedo in production and that successful running tests had been made the previous summer. Accordingly, the Allied study of countermeasures, which had been following along with the development of similar torpedoes, was put on a high priority. Soon the different possibilities mentioned in the Introduction had all been given some consideration.

An excellent towed NM was already in use for sweeping acoustic mines. This device consists of two steel bars, clamped parallel close together, which are pulled through the water in the direction perpendicular to the plane containing their axes. The water flowing between them causes the bars to strike against each other and give off much more acoustic energy than does a ship at all frequencies greater than 1 kc.[b] Both Great Britain and the United States proceeded to modify noisemakers of this type so that they could be towed at an adequate speed (at least 10 knots) and produce good sound output for a life of several hours. The parallel-bar type of noisemaker has subsequently been in general use by both navies.

By May 1943 the British had information indicating that the German torpedo homed at 20 knots with a minimum turning radius of about 100 yd and that its homing range might be as great as 1000 yd. They also suggested that the torpedo might be "forward-listening," in other words, that the hydrophones might be very insensitive to any sound approaching from near the torpedo's stern (in order to reduce the self noise from its propellers).

From this information the British concluded that two NM's should be towed 200 yd astern and separated by about 100 yd. As will be shown later, the

[b] An acoustic torpedo could not be sensitive to a lower frequency because a hydrophone system small enough to fit in a torpedo would not be sufficiently directional, that is, could not tell the side on which a noise was heard.

torpedo is very likely to overtake a towed noisemaker from the rear at some time in its gyrations and to pass over the NM and head toward the ship. With a forward listening torpedo there might be considerable danger that the torpedo would escape from a single NM at this time, hearing and overtaking the ship while keeping the NM in the insensitive arc astern. If, however, as it left one NM behind, the torpedo found another on its beam, this second NM could be relied on to take control. The simplest way to get this protection was to tow two noisemakers abreast, sufficiently separated to assure that whenever the ship was ahead of the torpedo there was also an NM within 110 degrees of the torpedo's bow. To provide separation the British began developing a diverter with the necessary rudders to tow an NM fastened below it at the required distance out of the ship's wake. They already had a parallel pipe noisemaker with a sound output 20 db over that of a ship and an endurance of 25 hr at 12 knots. The name FOXER was given to the complete set of this noisemaking gear, including two NM's, two diverters, and the towing hawsers.

In the United States a parallel bar noisemaker designated FXR was in production by July 1943. Preliminary theoretical studies had been made of the behavior of an acoustic torpedo under the influence of a ship and an FXR 500 ft astern. The tacit assumption was made that the torpedo could listen equally well in all directions. It was concluded that one NM could maintain control of the torpedo once the torpedo had reached it and that the only danger arose from torpedoes fired from directly ahead which were drawn in to, or very close to, the ship while homing on the FXR.[c]

During the summer some prisoner of war information[d] (later proved false) indicated that the hydrophones were along the torpedo's sides. This tended to substantiate the all around listening theory and the belief in the adequacy of one noisemaker.

Prisoners of war also stated that the torpedo was for use primarily against escort vessels, enabling the U-boat to disrupt a convoy's defenses. This possibility had not occurred to the Allies, probably because the screening vessels had never been a major target,[e] and because it was considered unlikely that the self noise could be reduced enough to allow a speed as great as 20 knots. Escort vessels now seemed the most logical targets for an acoustic torpedo, however. Their speed, maneuverability, small size, and the frequency with which they were bearing down on the U-boat and thus presenting a very small bow aspect, all tended to make escorts very poor targets for ordinary torpedoes. With a homing torpedo, however, all these disadvantages were cancelled; the higher speed gave a louder, and therefore larger target, while bow shots were possibly preferable to beam ones.

More effort was, therefore, expended on parallel-bar NM's suitable for higher speeds. The British ran into more difficulties with their cumbersome diverters, but the possibility of getting such gear used successfully seemed greater when it was to be handled by naval crews than by merchant vessel crews.

Such was the situation when the Germans were first ready to use their acoustic torpedo against the Allies. It was introduced on September 20-22, 1943, during the first full scale North Atlantic operation since May, namely the wolf pack attack on Convoys ONS 18 and ON 202. Three escorts and six merchant ships were sunk and an escort damaged; acoustic torpedoes accounted at least for the damaged escort and two of the other escorts. In contrast a German War Order claimed 12 escorts sunk, 3 damaged, and 9 merchant ships sunk, which indicates a high expenditure of torpedoes. Nevertheless, the torpedo proved itself a threat which might have been much more effective had the enemy been able to get more than two U-boats in contact with the convoy at one time. As it was, the potentialities of the torpedo caused the Allies extremely grave concern.

On September 23 the Admiralty issued a comprehensive appreciation of the use of the German acoustic torpedo. This included a review of the information available on the torpedo, a preliminary analysis of the first attacks (1 and 2 days old), tactical countermeasures, and a status report on FOXER, which was to be issued although it was hard to stream, short in endurance, hampering to maneuvers, and difficult to produce.

In the United States an extensive study of the countermeasure problem was begun. On the one hand reports on the torpedo's characteristics were

[c] Trajectories of this type are discussed on page 168.

[d] Much of the early information concerning the German acoustic torpedo was obtained from interrogation of prisoners of war. Unfortunately they did not in general know anything of its actual operation, so that it was necessary to deduce its method of operation from fragmentary observations which they had happened to make of its construction and use.

[e] Thirty-nine warships were sunk by U-boats between January 1942 and August 1943 in contrast to 1511 merchant ships.

collected and evaluated; on the other, development of a variety of noisemaking gadgets was undertaken. One of the early decisions was to discourage the development of impulsive noise sources with bursts less frequent than about 20 per second; these included rapid machine gun fire into the water and the grenade noisemaker composed of a series of explosive caps. It was felt that the torpedo probably would not respond to such a source, whereas if it did, a relatively steady source such as a ship would be able to override it even when providing a much weaker rms (or average) signal. Such discrimination would occur with the time constants which were most natural for a torpedo's amplifying and control circuits. This would not only be a good anticountermeasure device but would also (and more important) discriminate against the irregular peaks which are among the most undesirable features of a torpedo's background noise.

It soon became apparent, however, that a reliable evaluation of the performance of any particular countermeasure required a detailed understanding of just how the torpedo functioned. The two different assumptions which have been mentioned for ward listening and all-around listening lead to quite different NM arrangements. A careful analysis of the probable behavior of acoustic torpedoes was, therefore, undertaken. Its salient features are outlined in the following sections.

6.2.2 Torpedo Trajectory Analysis

The primary aim of a study of torpedo behavior is to determine the path which the torpedo follows — its trajectory — under the conditions that are of interest. In order to do this a means must be developed for rapidly predicting a torpedo's behavior in the presence of a particular NM system and under a particular set of assumptions as to an unpleasantly large number of torpedo characteristics, as will be apparent from the following discussion. Of obvious importance is the torpedo speed. It determines the ship speed necessary to outrun the torpedo. The torpedo trajectory can be expressed as a function of the ratio of the ship's speed to that of the torpedo.

Under the influence of a single noise source the torpedo can be assumed (to a first approximation) to attempt always to steer towards the source. This results in a straight path when the target is stationary, *e.g.*, an expendable NM. With the target at constant speed on a straight course the pursuit curve is a

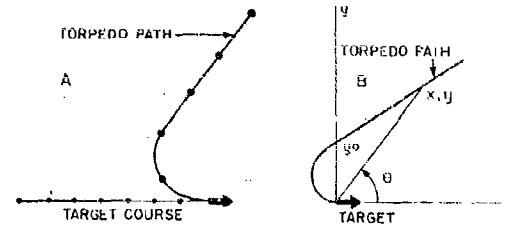


FIGURE 1. Typical tractrix. (A) In true space. (B) In relative space.

tractrix. Except for an adjustment in scale any tractrix is like that shown in Figure 1. With an (x,y) coordinate system centered on the target and the target heading in the positive x direction, the relative trajectory is given by equation (1).

$$x = \frac{y}{2}\left[\left(\frac{y_0}{y}\right)^{k} - \left(\frac{y_0}{y}\right)^{-k}\right], \tag{1}$$

or more simply,

$$y = y_0\left(\tan\frac{\theta}{2}\right)^{1/k}, \quad x = y\cot\theta$$

where k = ratio of target speed to torpedo speed,

y_0 = distance at which the torpedo first passes abeam of the target,

θ = torpedo's bearing relative to the target.

In stationary coordinates whose origin is the target's position at the time the torpedo is first abeam of it at distance y_0, the target's positions are given by equation (2), the tractrix by equation (3).

$$x = kt, \quad y = 0. \tag{2}$$

$$x = \frac{y}{2}\left[\frac{1}{1-k}\left(\frac{y_0}{y}\right)^{k} - \frac{1}{1+k}\left(\frac{y_0}{y}\right)^{-k}\right]. \tag{3}$$

When dealing with targets moving together, such as a ship and towed noisemakers, it is simplest to draw trajectories relative to this moving system. For each

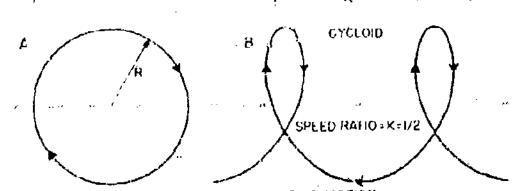


FIGURE 2. Course of torpedo when circling. (A) Fixed coordinates. (B) Relative coordinates (speed ratio = k = 1/2; ship motion →).

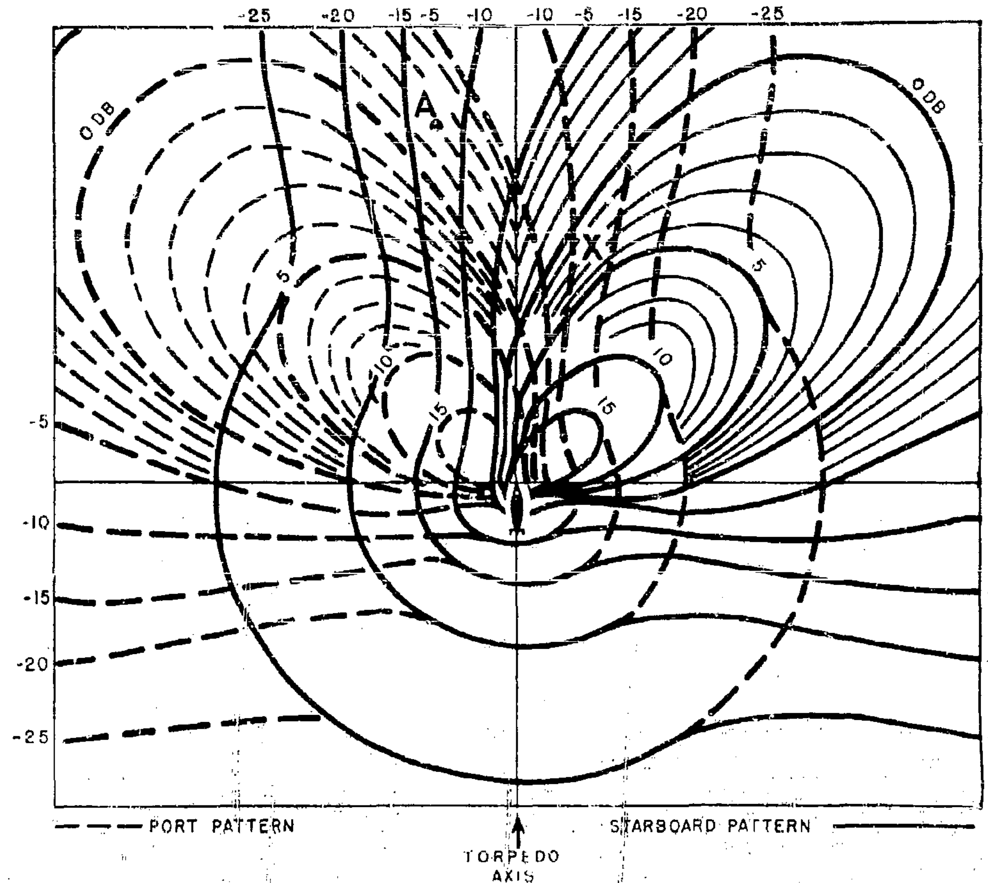


FIGURE 3. Typical sensitivity pattern.

value of k that it is desired to consider, a template sheet can be prepared, covered with a family of tractrices calculated from equation (1) so that by interpolation a pursuit course can be drawn from any point in to the center.[c] For any specific problem the trajectories can be traced from these templates.

A torpedo cannot always follow a tractrix, however, because its minimum turning radius may prevent it from making the sharp turn required. If the torpedo turns as sharply as possible when trying to get headed towards a noise source,[d] its path in relative space will be a cycloid rather than a tractrix. A typical cycloid is shown in Figure 2. Templates can be drawn for cycloids in the same way as for tractrices as an aid in drawing the relative diagrams.

The behavior of the torpedo depends upon acoustical and electronic features as well as speed and turning radius. In the fall of 1943 the exact characteristics of the German torpedo were unknown, but it was considered probable that a listening system was employed[e] and that the following general scheme of operation was used in order to determine from which side of the torpedo the sound arrived.

[d] Information in the fall of 1943 continued to confirm the fact that the enemy had enlarged the rudders of their G7e torpedo to give the acoustic torpedo a minimum turning radius of 80 to 100 m.

[e] A listening arrangement would be much simpler than one involving echo ranging and less subject to failure. It would probably have a greater homing distance. A torpedo would have little use for range information. The enemy had had much more experience with passive detection equipment. Most important, none of the intelligence information suggested echo ranging.

The rudder is controlled by the ratio of the voltages in two electric channels. If a steady sound source is moved about the torpedo at a constant range, the voltage in the port channel is much greater when the source is within some range of bearings on the torpedo's port side than when anywhere on the starboard side. Similarly, the starboard channel is most sensitive to signals from the starboard side.

In determining a trajectory, it is necessary to find out for each torpedo position just what are the relative voltages in each channel due to each noise source. To facilitate this another set of templates are drawn, one for each assumed sensitivity pattern. Each template is a transparent geographic plot to be centered on the torpedo position with the torpedo axis marked. By one curve it shows the locus of all points at which a standard (arbitrary) noise source would create a given voltage in the port channel and, by another, the same for starboard channel. Parallel lobes are drawn corresponding to sources each an integer number of decibels louder or softer than the standard. A typical sensitivity pattern of this sort is shown in Figure 3.

A standard noise source at point X in Figure 3 would give a signal of −12 db in the port channel and +2 db in the starboard. If, at the same time, a source 10 db louder than the standard (for example) is present at point Y, it would give a signal of 8 db in the port channel, and −5 db in the starboard. In order to obtain the total voltage in each channel with both present, the square root of the sum of the squares of the individual contributions is taken. This method should be sufficiently accurate unless a source is very intermittent, *e.g.*, a grenade exploding only ten times a second.

In constructing these templates it is assumed that the sound pressure is inversely proportional to the range from the source (6 db less per distance doubled). This is only an average value of the attenuation found in experiments, but the effects of considerable fluctuations can usually be shown to be negligible. The ranges involved at critical times are too small to allow the linear absorption of sound in open water to become important. However, there is evidence of considerable attenuation in the ship's wake, about 2 db per foot at 24 kc.[h]

The simplest sensitivity pattern is a circular one.

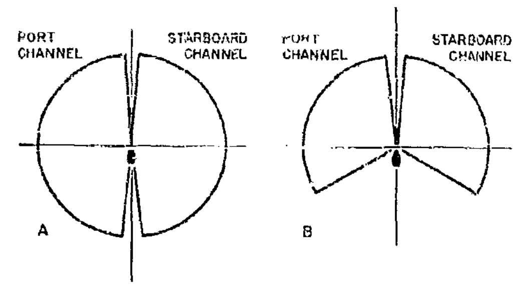


FIGURE 4. Simplified sensitivity patterns. (A) Circular pattern. (B) Modified circular pattern.

The template curves for each channel are semicircles on each side of the torpedo axis, as shown in Figure 4A. Dead zones of no differential are assumed to be present, but negligibly small, ahead and astern of the torpedo.[i] To break away from all-around listening it may be assumed that there is a wide angle of zero sensitivity astern, leaving the lobes as shown in Figure 4B.

A more realistic picture may be obtained by using another mathematical approximation which recognizes that the response of any hydrophone system will change smoothly with angle. If θ is the angle off the torpedo's bow, the contours of equal sensitivity can be expressed by $\cos(N\theta)$. The sensitivity will then be a maximum ahead (except for a negligible dead angle) and will decrease gradually as θ increases, becoming zero for all θ's greater than $\pi/2N$. A number of such patterns are shown in Figure 5. For $N = 1/2$ there is some listening at all angles except dead astern, whereas for $N = 1$ there is no response anywhere abaft the beam.

In an actual torpedo each channel may have its own set of one or more hydrophones directed toward one side. Alternatively the channels may be con-

[i] This pattern is essentially that assumed in the earliest United States studies mentioned in Section 15.2.1, this chapter.

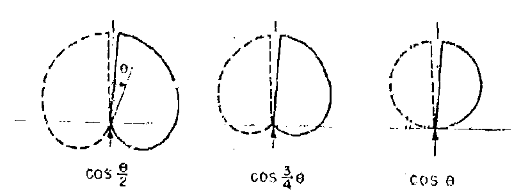


FIGURE 5. $\cos(N\theta)$ sensitivity patterns.

[h] In the initial trajectory studies, an attenuation of 0.1 db per foot was taken as a conservative assumption even at lower frequencies.

nected through phasing circuits to the same, or partially the same, group of hydrophones all facing forward. Either system would lead to the same kind of pattern. It is reasonable to expect that if an effort is made towards forward-listening, the maximum lobe for each channel would probably be rather broad and centered between 20 and 60 degrees off the bow. It is difficult to secure a rear response of either channel less than about 30 db below the maximum, no matter what the direction of the noise. There can be a rather large angle astern where a loud source would bring about approximately the same voltage in each channel. Accordingly a template can be drawn for a "practical" pattern having a maximum sensitivity 45 degrees off the bow and sensitivity 30 db lower in both channels throughout a 100 degree arc astern.[2]

This pattern is, in fact, shown in Figure 3. The pattern could be made sharper and the fore-aft discrimination greater if the frequency of maximum sensitivity were over 40 kc. This, however, would reduce the homing range as a result of the absorption of sound in open water, which becomes appreciable at such frequencies.

The rudder position should depend on the decibel differential between the two channels, that is, on the ratio of their voltages. Any control involving the absolute magnitudes of the voltages could not handle the widely different signal strengths to be expected. By the use of the templates and a curve expressing in decibel units the square root of the sum of the squares relationship, the signals in the two channels can be found in decibels above the same standard; these values can then be subtracted to give the differential.

The most plausible simple assumption as to the way in which rudder position depends on the differential is a "flip flop" type of control in which the rudder is thrown hard over whenever one channel has a given excess (say 5 db or more) and stays over until the other channel has the required excess. This flip flop control appears necessary for a forward-listening type of torpedo on the basis of the following argument.

Most torpedoes approaching from forward angles will miss a ship (with no noisemakers) on the first pass because they cannot turn sharply enough to stay on a tractrix and possibly because the principal target may actually be collapsing bubbles in the wake somewhat astern of the propellers. Having passed the ship's stern, many of these torpedoes will have the ship in the sector on their own stern where they can get no differential or even any signal over background. If, with no differential, the torpedo straightens out or returns to its original gyro course, it will never hear the ship again and be lost astern. On the other hand, with flip-flop control the missile will continue circling until it again hears the target. The same would happen about a single NM towed astern. Admittedly the torpedo would stay on its tractrix with less weave if on loss of differential it straightened out or, preferably, had "graduated control," that is, if the amount of rudder depended on the differential and thus on the bearing of the target off the bow. However, even with flip-flop control the weave should not be more than 10-20 degrees, and improvement in this would not compensate for the failure of so many bow shots.

The critical differential, designated by D, may reasonably be assumed to be 3 db. With a lower value there would be too much danger of undesirable rudder actuations. These might result from minor lobes in the sensitivity pattern astern, from fluctuations in the background noise, or from fluctuations in the transmission of the ship's sound. With these limitations, D should be as small as possible, because the larger D, the less the torpedo's homing range. As a torpedo approaches a ship from a distance under gyro control, background sound will initially predominate, causing approximately the same voltage in each channel. If the bearing to the ship is near the angle of maximum sensitivity for one channel, the voltage in that channel will increase as the ship is approached. The torpedo will turn towards the ship when the voltage in that channel due to the ship plus background is D db greater than that in the other channel, which is due to background plus a negligible contribution from the ship. If a greater D is required, the torpedo must approach closer on gyro before the ship noise can overcome background.

The maximum range at which a given ship flips the rudder changes greatly with the bearing θ of the ship off the torpedo's bow. The range is zero with the ship either dead ahead or (probably) in a large sector astern, that is, with θ's at which the sensitivity patterns for the two channels differ by less than D db. At other θ's the range depends chiefly upon the sensitivity patterns. For any choice of sensitivity pattern,

[2] A pattern of this sort was decided upon in the fall of 1943 on the basis of United States experience in the design of hydrophones and acoustic torpedoes.

of D,[8] and of ship intensity over background, a so called steering pattern can be drawn plotting the rudder actuation range against θ. Such curves are useful only when no NM is present.

The maximum of either lobe of a steering pattern gives the maximum range at which a ship can direct the torpedo. The value of this range depends on the noise output of the ship and on how well the torpedo's background noise has been suppressed. Neither of these quantities can be determined very accurately. Even for a given torpedo and a specific class and speed of ship there would be enough variation in ship output and in transmission conditions to make the range uncertain within a factor of three. It would obviously be unwise to base a countermeasure on an arbitrary actuation range.[9]

It is now possible to consider briefly the trajectories for which the torpedo was primarily designed, namely those against an unsuspecting ship. Assuming the torpedo to be a modification of the German electric G7e, the firing range was probably not over 6000 yd. Ranges between 1000 and 4000 yd would be the most likely. The initial gyro course would be a collision course for the ship, possibly for the ship's stern, in order to get the best chance of coming within homing range. When the torpedo reaches a point where the ship's noise can overcome background noise (as shown by the ship's stern reaching the appropriate contour on the steering pattern centered on the torpedo), the missile turns toward the ship. If this happens at short enough range, the torpedo might hit the ship before turning far enough to head at the stern, as shown by trajectory A, Figure 6. Alternatively, assuming flip-flop control, the torpedo will turn until the screws have passed through the dead angle of small differential on its bow and have reached the opposite lobe of the steering pattern where the other channel has a D db excess, causing the rudder to flip. With a forward listening pattern and mechanical time constants of the order of 1/10

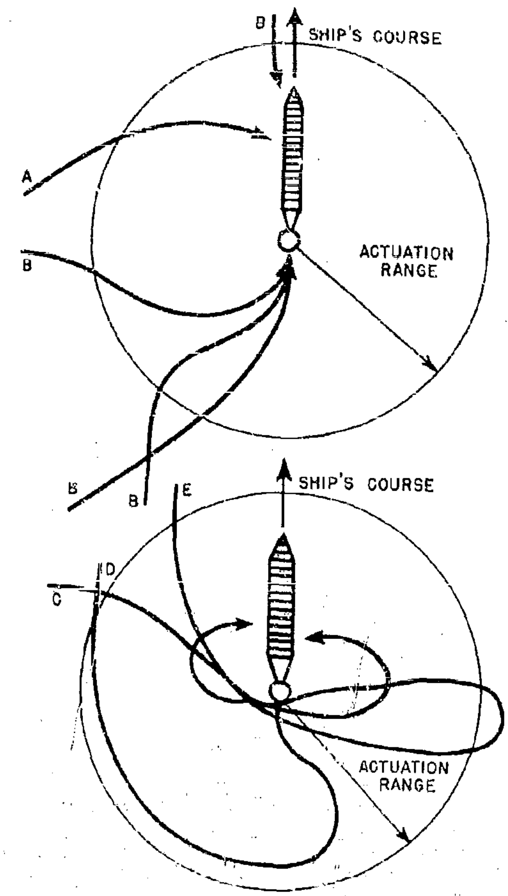


Figure 6. Trajectories relative to ship.

sec, the course reversal should occur with the target less than 10 degrees off the bow. By repetition of this procedure the torpedo follows a tractrix towards the screws with a small weave. Trajectories marked B in Figure 6 are examples of such tractrices.

If the tractrix approaches from dead ahead, the torpedo may hit the ship before coming abeam the screws. If the tractrix is entered sufficiently far astern, the torpedo will follow it all the way in, making a hit on the ship's stern. In the intermediate cases, including most shots fired from forward of the beam, the torpedo is not able to keep headed for the screws because the radius of curvature of the tractrix becomes less than the torpedo's minimum turning radius. On the (x, y) coordinates of Figure 1 relative to the source the loci of such points are two circles tangent to the

[8] It was once thought that there was a good chance that the D required to take the torpedo off gyro would be greater than that needed for the later steering. Using this "gate" would sacrifice some homing range in order to prevent a temporary peak in ship noise from taking the torpedo off gyro course and leaving it circling at such a distance that the normal ship noise could not be heard. However, the gate was assumed not to exist since its presence was found to be if anything an aid to countermeasure.

[9] Various estimates were made of the actuation range of the German torpedo, ranging from 100 to 1000 yd for a typical ship target. Later tests suggest the higher figures to have been the better.

y-axis at the origin and of radius $\frac{1}{2}KR$, where R is the turning radius of the torpedo.) The torpedo is forced to lose ground astern, usually missing the ship on the first pass. Even though the ship may now be in the dead zone astern of the torpedo, the flip-flop control will cause the missile to continue circling forward. It may hit the ship's side before it has circled far enough to be headed at the screws, as in trajectory C, Figure 6. Otherwise it will make another pass at the screws, usually on a rear tractrix leading to a stern hit, as in trajectory D. In all cases a hit occurs on at most the third pass, as in trajectory E. Any trajectory can, like those of Figure 6, be drawn relative to the ship by tracing from the appropriate tractrix and cycloid templates.

15.2.3 Theoretical Trajectories and Noisemakers

Next to be considered are the trajectories which arise when a single noisemaker L db louder than the ship is towed under the wake about 200 yd astern. The submarine's firing procedure would be the same as for the ship alone, but the torpedo would get on a tractrix towards the noisemaker at ranges of a mile or more, if L is 12 db or more. Thus any torpedo in working order is drawn into the system. The ship's sound cannot influence the torpedo except within about 50 yd of the screws as long as the NM is on its forward bearing. Thus the paths to the NM are similar to those to a ship by itself.

A direct hit occurs when the torpedo is drawn into the ship while steering towards the NM. Such hits result from tractrices which happen to go through the ship. These hits are independent of the NM strength or distance astern. To have a good chance of making such a hit the firing submarine must be directly ahead of the ship, not more than about 5 degrees off the bow. Conversely, the ship can be made safe from them by never heading directly at the submarine.

If the NM is too weak or too far astern, a forward-listening torpedo fired from about 10-20 degrees off the ship's bow may make an indirect hit. This occurs when the tractrix comes close enough to the ship that the torpedo is forced to circle out of the tractrix across behind the ship's stern and then to pursue the ship to a stern hit keeping the NM in the dead angle astern. Path A in Figure 7 shows a trajectory which might lead to an indirect hit. For the following explanation assume that the torpedo is weaving towards the NM past the ship's port side. While turning to the left in the weave, the left channel may receive a signal from the ship which is within D db of that received in the right channel from the NM. (This is determined by employing the sensitivity pattern template as described in Section 15.2.2.) If, as a result of the proximity of the screws, this occurs even when the NM is at the angle of maximum sensitivity for the right channel, the differential D is never obtained, and the torpedo continues to circle left as shown in Figure 7. During the turn the NM's bearing off the torpedo's bow increases steadily through angles of decreasing sensitivity. Meanwhile in the dangerous cases the bearings to the screws (on the other side) increase less rapidly and the range to the ship decreases, all tending to keep the torpedo circling. This condition continues if the torpedo has space in which to turn sufficiently (about 90 degrees) before crossing the wake. Eventually it will be heading towards the screws with the NM in its dead angle astern and will be guided in to a stern hit. If the

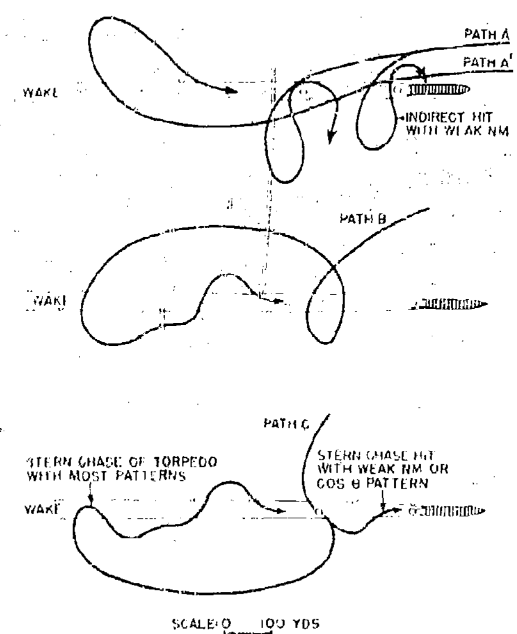


Figure 7. Typical trajectories relative to a 12 kt ship with single towed noisemaker.

To allow a margin of safety a directive was issued specifying that when possible any submarine be kept more than 10 degrees off the bow of a ship towing FXR.

tractrix is too close to the ship, however, as in Path P of Figure 7, the bearing to the ship increases rapidly at about the time of crossing the wake and the NM regains control.

Thus there may be a dangerous group of tractrices close enough to the ship for the latter to deflect a torpedo but far enough away to allow it sufficient circling space. The danger of indirect hits can be eliminated by making the NM sufficiently loud to prevent the torpedo leaving any tractrix which is far enough from the ship to give circling room. Any reduction in torpedo turning circle therefore obviously increases the danger from such shots. For the cos $(1/2\,\theta)$ patterns or "practical" sensitivity patterns, the F required of an NM 200 yd astern is about 10 db.

Torpedoes which have made neither direct nor indirect hits continue to the NM, as shown in Figure 7. As with a ship alone, some approach the NM from the rear, making a so-called stern chase. The others pass astern of it, circling forward with minimum turning radius. These shots circle across in front of the NM and continue circling, falling way behind the NM and entering a stern chase. All trajectories lead to a stern chase after at the most four passes at the NM. By employing various sensitivity patterns, it can be shown that during this preliminary weaving about the NM the ship cannot capture the torpedo provided the NM is as much as 200 yd astern and is able to hold the torpedo after a stern chase.

The success of a single noisemaker arrangement thus depends on its ability to prevent a torpedo which has just passed over it on a stern chase from continuing on to hit the ship. The most critical factor is the torpedo's sensitivity pattern.[a] There is no problem if the torpedo can hear about equally well in all directions, as was assumed in the earliest United States studies, since the NM, being louder and closer, is certain to be heard over the ship and to make the torpedo circle to the rear, where it would start another futile stern chase. No matter how loud the NM, it cannot be depended upon to counter a "mathematical" pattern with a sector astern in which the sensitivity is zero (no listening whatsoever), such as that in Figure 1B. The NM is likely to fall into the dead zone and stay there while the ship noise guides the torpedo to a hit.

[a] Since accurate detailed knowledge of the German acoustic torpedo's sensitivity pattern has not been available, there has always been doubt on the subject of safety from stern chases. This has, in fact, been the crux of the countermeasure problem.

The cos $(1/2\,\theta)$ pattern, however, with the sensitivity greater than zero everywhere but right astern, is countered by an NM louder than the ship by 19 db or more. In this case attenuation of the ship's noise in the wake is sometimes needed to cause the torpedo to turn sufficiently for the NM to regain control. With an estimated 0.1 db per foot for the attenuation there is no chance that a torpedo in the wake and back near the NM could hear the ship. This protection is not diminished if the NM should happen to be to one side of the wake rather than underneath it.

The more realistic practical sensitivity pattern gives new assurance of the value of a single NM. Having passed over a sufficiently loud NM on a stern chase, a torpedo with a practical pattern receives so much signal in both channels from the NM that the additional ship sound in one channel cannot provide the necessary differential to flip the rudder. With flip-flop control the torpedo stays in the circle it happened to be in as it crossed the NM until it falls way behind. For an NM towed 570 ft astern an output of 12 db above the ship can be shown to be adequate. The required output decreases slightly with increased ship speed because the torpedo's distance of closest approach to the ship is increased.

On the basis of early recommendations, FXR was being prepared during the fall of 1943 with 200 yd of cable. The cable sag resulted in a towing distance of 570 ft. The completed trajectory study, made following the above outline, revealed no reason for changing this. A longer tow would require a higher output to prevent indirect hits and would increase the difficulties of handling the gear. A shorter tow would require a higher output to prevent stern chase hits. It would have been nice to tow the NM beyond the homing radius of the torpedo on the ship. This was precluded, however, by the uncertainty of this radius and by the greater NM output required to prevent indirect hits if, as is likely, the radius is over 200 yd. The FXR had to be "depressed" below the bottom of the wake so that its sound would not be muffled in any direction. There was, however, no harm in its towing somewhat to one side of the wake while still maintaining its depth.

Consideration was given to a noisemaker fixed with respect to the ship but on some bearing other than astern. These other positions, which might have been accomplished by concentrated machine gun fire, seemed to be inferior. The chance of direct hits increased since the ship cut across more tractrices.

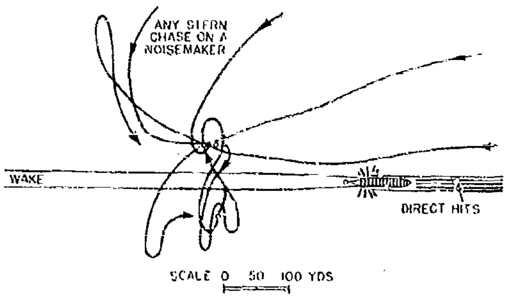


FIGURE 8. Typical trajectories relative to a 16- to 18-kt ship with two towed noisemakers. Similar trajectories from starboard side.

For safety from indirect hits it was necessary to keep the NM within 300 yd of the screws. Most important, the ship was in a better position to capture the torpedo as it circled back from the NM. Finally, the sonar interference would be increased.

Trajectory analysis confirmed the conclusion that two NM's towed abreast gave a more certain countermeasure than a single FXR. The advantage of the British double FOXER lay in its elimination of practically all the ambiguity with regard to stern chases. Even a torpedo with zero sensitivity abaft the beam (e.g., the cos θ pattern in Figure 5) could be relied upon, after it has passed over one NM, to be drawn to the other before getting too close to the ship, as shown in Figure 8. During the initial approach the FOXER system is equivalent to one NM with the same total output. The torpedo is either on a trajectory toward one of the NM's or towards the "acoustic center of gravity" between them. Thus the chance of a direct or indirect hit is essentially the same for the double FOXER as for a louder single FXR.

Highest priority was given to the development of adequate diverters. However, as the British were finding out, the production and handling difficulties seemed to be extremely great with FOXER. Since most of the evidence indicated the adequacy of a single NM, the decision was made by the United States to issue FXR. Emphasis was placed, however, on the importance of examining each bit of new evidence to make sure that this decision was not invalidated.

15.2.4 Detailed Intelligence Concerning the German Torpedo

As the ideas described above were being worked out in detail during the fall of 1943, further information was accumulated on the operation of the German torpedo. In mid-October a detailed and apparently accurate description of the T-4 acoustic torpedo was obtained from a prisoner of war [P/W] whose last cruise had started on July 20 with three T-4's aboard. He also reported that an improved model, the T-5, was expected for operational use in August. The T-4 was a modification of the electric G7e torpedo slowed to 20 knots and with larger rudders to give it a 90-m turning radius. A liquid-filled plastic nose enclosed two forward-facing hydrophones. In a pre-installation test ("Spatz" test) the rudder was seen to have three positions, hard over on each side and occasionally central, as a noise source was moved about the nose. A switch was to be set on either "WS" or "NS" at the time of firing. This switch had an undecipherable effect on the acoustic rudder control, which did not become clear until much later.

Another prisoner of war who had observed running tests of the torpedo in the Baltic confirmed the general features of our trajectories, but added a noticeable weave. This tended to confirm the belief that flip-flop control was used.

With the prisoner of war's description of the T-4 nose as a starting point, arrangements were made to reconstruct the hydrophones in order to obtain their sensitivity pattern. By December preliminary results indicated that the T-4 had velocity hydrophones connected by phasing circuits and sensitive at about 5 kc. The sensitivity pattern would only be about 25

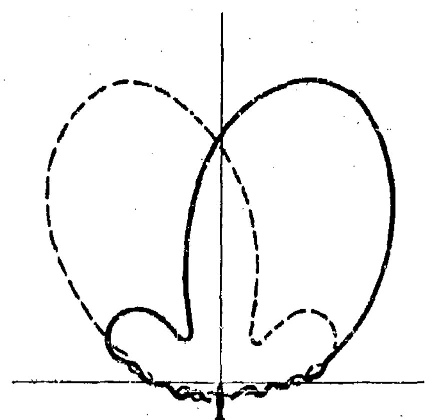


FIGURE 9. Sensitivity pattern of reconstructed T-4 hydrophone system.

db down astern. All this was welcome news, tending to confirm the practical pattern, though complete measurements were not made until somewhat later.

All was not rosy, however. Measurements were made with equipment which immediately broke down permanently; these tentatively indicated that the ship's own sound was not attenuated in its wake at frequencies below 10 kc. Thus the wake could not be depended upon to turn the torpedo after a stern chase. Full reliance had to be placed on the sensitivity's not being more than 30 db down astern.[a]

Scattered information was indicating that the T-5 was in use and that it had a speed of 24½ knots. This increased the importance of trajectories involving low speed ratios and also increased interest in how self noise had been reduced. One of the more fantastic reports claimed that for acoustic insulation and extra explosive power much of the torpedo had been stuffed with guncotton! There seemed to be two models of T-5, one with a round plastic nose like the T-4 and the other with a flat nose. Imbedded in this flat metallic surface were four parallel laminated bars 10 by 2½ cm, their long dimensions vertical. These were thought to be the surfaces of four magnetostriction hydrophones. It seemed likely, however, that there was a phasing system between the hydrophones. Their spacing indicated a peak response at about 12½ kc.

There was definite evidence of a magnetic attachment to the T-5's pendulum-type inertia pistol. Several ships had reported explosions in their wakes which were ascribed to malfunctioning of the inertia pistol. Prisoners of war claimed that this had been corrected. The magnetic feature increased slightly the chance of a direct hit and, more important, allowed the depth setting to be as much as 10 ft below the keel. This lower depth should have considerably decreased both the chance of broaching and the self noise. In addition, explosions beneath the ship's keel would be much more damaging than at the side of the hull. Thought was given to creating a magnetic field about the FXR to detonate the torpedo.

In late January a complete experimental sensitivity pattern was obtained from the reconstructed T-4 nose. It seemed likely that the round-nosed T-5 possessed this same pattern. It conformed to the assumed practical pattern in that each channel had its maximum sensitivity 25 degrees on its own side of the bow and its sensitivity at no angle dropped more than 28 db below this maximum. However, each channel had a prominent secondary lobe at about 60 degrees on the opposite bow, which even with the best adjustment could not be brought more than 2 db below the main lobe of the other channel. At all bearings greater than 60 degrees the patterns for the two channels remained within 7 db of each other. They crossed over each other in a quite random fashion, as shown in Figure 9. The differential D required for steering would have to be 7 db to prevent false or confused steering, *e.g.*, turning to port when the target was about 110 degrees off the starboard bow. Nevertheless it was thought possible that in order to get a greater homing range the enemy might have chosen $D = 3$ db, counting on the low sensitivity astern to prevent confusion by hiding the ship's noise in the background. Whatever the D, only a source between 5 degrees and 60 degrees off the bow could be certain to flip the rudder in the correct direction.

This pattern improved the stern chase situation but increased the danger of an indirect hit. The lower fore-aft discrimination and the likelihood of a greater D made it more difficult than with the practical pattern for the ship to take over the torpedo after a stern chase. On the other hand, a louder NM was required to prevent the ship from attracting a torpedo out of a nearby tractrix. If this torpedo circled far enough for the NM to be more than 60 degrees off its bow, it would continue circling no matter how poorly it received the ship's sound. Usually when it got headed toward the screws it would be in a position to go in for an indirect hit. A directive was issued to the effect that any U-boat should be kept more than 20 degrees off the ship's bow. By forcing the tractrices farther from the ship this procedure would eliminate most indirect hits as well as all direct ones.

By January 1944 FXR Mk 2 (suitable for speeds from 12 to 19 knots) was getting into general use

[a] The British even proposed a complicated hypothetical rudder control for T-5 which would be able to make a stern chase far over an NM despite the 30-db restriction. The phasing system between the hydrophones was sufficiently complicated to be able to distinguish between loss of contact when the torpedo passes over a noise source and loss of contact when the torpedo passes beside the source. In the first case the rudder would straighten until differential was again obtained, so that having made a stern chase on an NM the torpedo continues toward the ship without circling. In the second case the rudder locked over in the direction of the source, thus assuring more than one pass at a ship by a shot from ahead. This proposal seemed too complicated to be practical. In addition, the slight weave of the torpedo on a stern chase would often cause it to pass somewhat to one side of the NM, possibly causing the rudder to lock over.

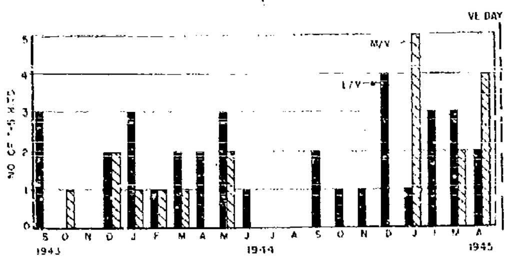


FIGURE 10. Number of hits by German acoustic torpedoes by months (escort vessels solid; merchant ships crosshatched).

aboard the larger escort vessels. For lower speeds FXR Mk 3 was being issued to smaller craft. The chief operational difficulties with FXR Mk 2 arose from the limits imposed upon the antisubmarine vessel's speed and from the depressor (employed to keep the NM below the wake). There were also conflicting reports as to whether the production models had the specified 12- to 15-db excess in output over the ship. A safety factor of several decibels was certainly desirable. With much trial and error a 30-inch parallel pipe NM was developed which could be towed at any speed from 8 to 25 knots. It was depressed by a 90-lb weight called a "minnow." Its output was steadier than that of FXR Mk 2 and was, at 5 kc, 20 to 25 db above the average destroyer escort (DE); this compared favorably with the Canadian CAT gear and the components of the British FOXER.

Meanwhile, care was taken to investigate all torpedoings in an effort to determine the part played by T-5's. Figure 10 records for each month the number of incidents which were designated as probable T-5 hits on the basis of intelligence available before the German surrender. (Complete German records are still not available.) The importance of towing NM's in dangerous regions was emphasized by the high proportion of escort incidents (7 out of 11 through May 1944) in which the presence of the U-boat was unsuspected until the range was less than 2500 yd. In these cases no other countermeasure could have been effective. The sudden burst of antisubmarine ships hit in May 1944 included one case with FXR Mk 2 being towed. The newly developed gear was soon issued and was designated FXR Mk 4.

In the spring of 1944 a copy of a T-5 firing table was recovered from a U-boat scuttled off India. By substitution into firing triangle relationships the torpedo's speed was confirmed to be 24½ knots, at least on the initial gyro run. Investigation of the minimum firing ranges (tabulated as a function of the target's firing course and speed) revealed that the torpedo had a 500-m enabling run, that is, it was set so that the hydrophones could not control the steering until 30 sec after firing. This was to help prevent the torpedo from homing on the U-boat. The minimum firing range was specified so that after this 500 m the screws would still be at least 200 m ahead; then there was no chance of the forward looking lobes not hearing the ship.

Although information concerning the torpedo was thus growing steadily, it was still rather fragmentary and unsatisfactory in the spring of 1944. This was soon to be changed.

15.2.5 Studies of Captured T-5's

On June 5, 1944, USS *Guadalcanal* and escorts captured U-505 with two round nosed T-5's aboard. The first examination of these torpedoes showed that inside each plastic nose there were not only two hydrophones and some liquid but also a rubber horn structure directing each hydrophone 30 degrees off the bow. Each hydrophone governed a channel without phasing. The maximum sensitivity of the whole system was at about 27½ kc, considerably higher than had been thought. This higher frequency was all for the good since NM output had been found to drop off less rapidly with increasing frequency than did ship noise. Thus FXR Mk 4 was about 30 db over a DE at 27½ kc.

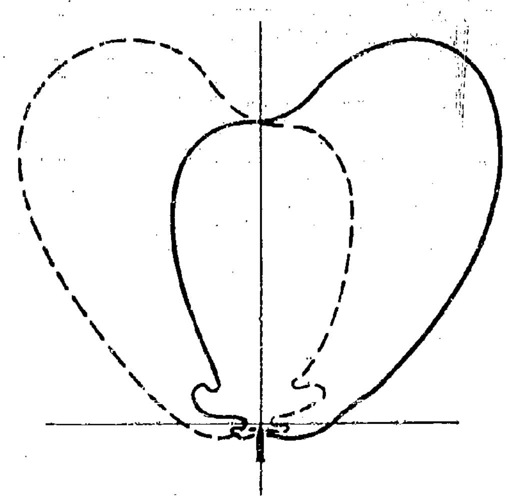


FIGURE 11. Measured sensitivity pattern for captured round nosed T-5 from U-505.

By August measurements of the sensitivity pattern revealed a more unpleasant surprise. The response astern was 42 db below the maximum! It followed that there was some chance of stern hits with FXR Mk 1, especially since D, the differential needed to flip the rudder, seemed to be only 2 db. On the other hand, the patterns for the two channels, shown in Figure 11, were well separated (by about 12 db) between the angles of 20 degrees and 125 degrees off the torpedo's bow. This together with the low D and high NM excess eliminated the danger of indirect hits. In fact there were no indirect hit trajectories even with an NM 400 yd astern. Since the longer tow gave better protection from stern chases, adding more cable would have been recommended, had actual running tests with the T 5's not been expected very soon.

Such tests were particularly necessary because of a new complication which was discovered. The torpedo was found to have a common amplifier into which the two channels were switched alternately 108 times a second. If the signals were equal there would be no 108 cycle component in the output. Otherwise the phase of this component indicated which signal predominated. Trouble arose from the fact that FXR Mk 1 pipes struck together with a frequency from 90 to 115 cycles. What was the torpedo response to a signal with this modulation? The answer was complicated by the effect of the automatic volume control [AVC].

Some questions were, however, definitely answered by inspection of the torpedoes. The meaning of the "WS" and "NS" settings had been pretty well deduced from prisoner of war information. Now there was confirmation. WS was set on a torpedo being fired from within 90 degrees of the target's bow; this required that when differential was lost the torpedo would continue in its minimum turning circle—that is, flip-flop control. NS was used on rear shots and made the torpedo return to its original gyro course after receiving no differential for several seconds; when differential D was again received the rudder would again go over.

The reason for having both settings seems to lie in the fear that the torpedo, as it approaches a ship from a distance, might start circling as a result of a temporary increase in noise level but before it could receive a steady signal from the ship. This was acceptable on forward shots since the ship's motion was likely to close the range to where homing could start and since flip-flop control was needed if the torpedo should miss the stern on its first pass. On stern shots the flip-flop was not needed because the torpedo could stay on its tractrix. Resuming gyro control after a temporary signal was likely to bring it into homing range of the retreating ship, whereas circling would leave it hopelessly behind.

A consequence of this control system was that even if WS shots were successfully prevented from making stern chase hits, there might be danger of such hits by torpedoes fired on NS from within 30 degrees of the ship's stern. These NS trajectories on passing over the NM into a region of no differential would take up a gyro course which would take them towards the ship to a position from which the screws could guide them in to hit. An NS torpedo fired from farther off the stern would return to a gyro course from which it could never hear the ship or, when it did, it would turn far enough to stern to be recaptured by NM.

Preliminary running tests with the torpedoes revealed a turning radius of 80 yd and a speed of 22 knots on turns and confirmed 24½ knots as the speed on gyro control.

During October, one year after the first intensive countermeasure studies, detailed observations were made on 20 acoustic runs with the T 5's apparently in proper operating condition. FXR Mk 1 provided good protection. FXR Mk 2 proved equally effective except on one run during which its output was erratic. The explanation of this good news lay in the very large weave with which the torpedoes approached these NM's. The torpedo's beam was often presented to the NM before the rudder flipped to carry the missile into the next phase of the weave. When the ship speed was 15 knots or over, the torpedo was not able to overtake the NM but weaved back and forth behind it. With a slower target the T 5 was able to circle in ahead of the NM occasionally, but always at such an angle that the NM continued to control it, at least until it had fallen behind the NM again. There were no passes directly over the NM. Most runs were on NS with the gyro course parallel to the ship in order to have conditions most favorable for a stern chase hit. Even this did not cause trouble. The ship's wake was so narrow compared with the weave amplitude that it had no effect. No feature of the trajectories could be correlated with the NM's striking frequency, although in one case there were less than 2 cycles between the striking and the torpedo-switching frequencies.

The large weave increased the angle off the target's bow from which a torpedo might be fired and still make a direct hit. A torpedo fired 14 degrees off the bow made such a hit, but three shots from about 20 degrees missed by 100 ft or more. It seemed that the existing doctrine (a precaution against the now non-existent *indirect* hits) of keeping the U-boat more than 20 degrees off the ship's bow allowed a sufficient margin of safety against these direct hits. A statistical analysis of the weaving paths verified the rule of 20 degrees. Because the weave amplitude increased as the torpedo approached the NM, it was found that shortening the FXR towing distance from 200 yd would markedly *increase* the danger of direct hits. On the other hand, using a 400-yd tow would only slightly improve matters.

Three runs were made against a 16-knot DE (35 db spectrum level above 0.0002 dyne per sq cm at 200 yd) without an NM. The weave on stern approaches was quite small, the ship seldom getting more than 20 degrees off the torpedo's bow. This was enough, however, to reduce the speed made good to about 19½ knots, so that a ship making 20 knots or more should be safe from all but shots down the throat.

On one of these runs the torpedo turned toward the ship leaving gyro control at a range of about 1500 yd. Whether or not this was a fluke, the homing range was definitely over 600 yd, since the torpedo, on being enabled at this range, steered directly for the ship. A 1500-yd homing range would make tactical countermeasures at speeds of 10-18 knots (step-aside procedures) extremely risky.

On the basis of the performance of FXR Mk 2 in the running tests, development was initiated on an NM with a steady output about that of a good FXR Mk 2, i.e., about 20 db over the ship. This gear was to be substituted for Mk 1 whenever the latter's interference with sonar was a serious handicap. However, no satisfactory design was found.[f]

During the fall the electronic parts of several flat-nosed T-5's were found in France and sent to England. As had been predicted the hydrophones were combined by phasing circuits into two channels. The maximum sensitivity was at 27½ kc. The amplifiers were of a different type from those found in U-505's round-nosed torpedoes. It was established, however, that either the flat-nose or the round-nose hydrophone could be used with either amplifier. Since the German firing instructions made no distinction between models, it seemed likely that there should be little difference in their performance. With this information and encouraged by United States running tests the British in December authorized the use of Uni-FOXER, a single NM system.[g] However, since no explanation of the large weave was available and since it was thought that the large weave might not occur with the newly discovered amplifier, the Uni-FOXER was towed at 400 yd.

The large weave was not explained until after the war, when an extensive study of the round-nose T-5 electronic system was completed. The differential D required to flip the rudder was found to depend on the type of noise source and upon its intensity. D was only 2-3 db with ship noise, which was essentially thermal noise with a peak to rms ratio of about 11 db. D was considerably greater for parallel pipe noisemakers, however, whose peak to rms ratio was about 20 db (in deep water). This D rose to over 12 db when the hydrophone output was in the high voltage range corresponding to a signal 55 to 85 db above 0.0002 dyne per sq cm from the direction of maximum sensitivity. This corresponds to ranges of 800 to 30 yd from a 15-knot FXR Mk 1. Since at no bearing were the sensitivity patterns of the two channels more than 12 db apart, the rudder could not respond when the signal was so loud. Thus the torpedo kept turning until the NM was so far off its bow that the hydrophone output was reduced to where steering differential was obtained. This might not happen until the NM was on the torpedo's beam. Thus the large weave resulted. The response was found to be more erratic when the NM striking frequency was close to the switching frequency. The AVC, the switching circuit, and the assorted time constants all contributed in such a complicated way that further analysis here is not warranted.

[f] Sonar interference from Mk 1 was at times so troublesome that a device was developed to turn it off completely when desired, designated as Flap. The noise output of Flap can be turned off or on by quick slackening of the towing cable. It should be kept in mind, however, that stopping the NM exposes the ship not only to torpedoes fired during the quiet period but also to torpedoes fired within 10 minutes prior to its stopping which may have been pursuing the NM. Most WS torpedoes which had been trapped by the NM would then hear and attack the ship.

[g] The British double Foxer always had serious practical difficulties, but a simple Foxer diverter (Scate) had been developed in the United States by the end of World War II which should make a two-NM scheme feasible.

Experiments with FXR noise equal in both channels and with ship noise superimposed in one (simulating the critical conditions after passing an NM on a stern chase) showed that the ship could flip the rudder when its rms contribution was about equal to the rms FXR level in both channels. This meant that without the weave a D of 3 db could be counted on in the stern chase; the earlier calculations based on a D of 1.2 db were pessimistic. Study of the circuit diagram of the flat-nosed T-5 amplifier suggested that, even if it did not give a weave, it quite possibly would respond to peaks of FXR signal rather than to the rms value. FXR Mk 1 should then have a good chance of drowning out the ship on a stern chase.

With present information, were it not for the large weave a quiet NM such as Mk 5 could not be advocated, and towing FXR Mk 1 at 400 rather than 200 yd would provide a desirable margin of safety. Had World War II continued, running tests with the flat-nose torpedoes would have been very much worthwhile, but the German surrender was in itself a completely adequate countermeasure.

15.3 OPERATIONAL DATA

The success of our countermeasures could not be judged accurately from our own operational data, since they are largely restricted to cases in which the torpedo hit. We have no record of most of the failures. Nevertheless certain data are of interest. By V-E Day 51 torpedoings had been designated as probable T-5 hits. Figure 10 gives the data on a monthly basis. As the U-boat effort declined, the low but constant contribution of T-5's became more important. In the last months of the war serious consideration was given to the problems of issuing NM gear to merchant vessels. Table 1 summarizes the available information on incidents thought to involve T-5's.

Of the seven ships hit while towing NM's, one had FXR Mk 2, one FXR Mk 1, two British Unit FOXER (in poor condition), and three had Canadian CAT. At least two of these cases were most likely to have been direct hits.

The T-5's which made hits on antisubmarine ships were not so successful as other torpedoes in sinking their targets. This may probably be associated with the high proportion of T-5's which struck near the stern (63 per cent for antisubmarine ships, 53 per cent for merchant vessels), since this often resulted in only local damage which could be kept under control.

It is hoped that a much clearer picture of NM effectiveness will be obtained from study of German Admiralty IBM cards. These cards give facts pertinent to each torpedo expended (by U-boats which got home to report). Interrogations have yielded a wide variety of estimates of the number of T-5's fired and their success. It is clear, however, that only a small percentage of the torpedoes expended hit their targets. There were probably many duds, as is likely with such a new and complicated device. The enemy must have attributed some failures to our noisemakers. It has been reported that orders were issued that when an NM was near, T-5's should not be fired unless the U-boat was almost in the target's wake. If this order was followed, the NM's served their purpose in a very simple manner.

TABLE 1. Use of German acoustic torpedo T-5. (September 9, 1943–May 8, 1945.)

	Type of target	
	Antisubmarine ship	Merchant vessel
Number of probable T-5 hits		
With a towed NM	7	0
With target speed under 9 kt	3	1
Probably without countermeasures	22	18
Total	32	19
Percentage of all incidents that were probable T-5 hits	10	[illegible]
Percentage of T-5 hits causing sinking	41	79
Percentage of other hits causing sinking	84	89

EPILOGUE

FOREGOING chapters have discussed the antisubmarine aspects of World War II in some detail, both as a history and as an object lesson in rational naval tactics. This would not have been done if it were not feared that a future war might at some time present similar problems. Yet the nature of any hypothetical future submarine and antisubmarine operations is now so uncertain that any discussion of them is highly speculative in character.

It is evident that this volume on antisubmarine warfare has been essentially historical in nature. It has retailed facts and figures from experience collected in the 6 years prior to V-J Day and developed theories to explain and interpret them. Its basis is therefore a dual one, the characteristics and tactics of the German U-boat on the one hand, and those of Allied antisubmarine craft on the other. Had the contestants been different ones, the course of the war would have been altered correspondingly.

The outstanding characteristics typical of the German U-boat throughout most of World War II were related to the policy of surfaced operation. Their offensive tactics were predicated on the use of visual detection and tracking on the surface with high speed and maneuverability. Diving was resorted to only in emergency to escape detection or attack. The large wolf packs formed against North Atlantic convoys were characteristic of their emphasis on coordination. Their consequent heavy radio traffic provided important information to the Allies, and their weakness in radar detection techniques gave the Allies a telling advantage against the surfaced U-boat.

On the Allies' side the overriding importance of maintaining North Atlantic convoys to Britain did more than anything else to determine the general course of the antisubmarine war. This was the central battle, with a great variety of diversionary forays and skirmishes spread over the remainder of the oceans. To defeat the U-boats their weak points were exploited to the full, especially by radio direction finding position estimates and effective use of radar, both surface and airborne.

The picture would no doubt be different in any future war, for many important changes were in progress during the closing period of World War II. These trends are the most obvious indication of what may be expected in the future.

After the defeat of the U-boats in the summer of 1943, the Germans initiated an extensive program of research and development on methods of U-boat warfare. The high-submerged-speed submarine was probably the most striking result. The ultimate objective was a submarine with turbine propulsion, burning fuel oil with hydrogen peroxide as an oxygen source (the Walter turbine). This was to be the Type XXVI U-boat with a maximum submerged speed of 25 knots for 6 hours instead of 8 knots for 1 hour like the standard type of U-boat. The tactical value of such a speed in attacking convoys and in avoiding search and counterattack would obviously be very considerable. Although the feasibility of Walter turbine propulsion had already been demonstrated at that time, no Type XXVI U-boats were ever built because of production difficulties.[a] Several smaller boats, Type XVII, were built, however, for experimental purposes, and trials were in progress by V-E Day.

Less spectacular than the turbine drive U-boat was the high-speed electric drive Type XXI. They were highly streamlined boats with powerful electric motors and high-capacity batteries. The resulting capabilities were a top speed of 15–18 knots submerged for a brief period, and of 10 knots submerged for about 10 hours. U-boat construction was concentrated on the Type XXI during 1944 and considerable numbers of them were ready to start operations in May 1945. No war patrols had actually been made, however.

Both of these types were, of course, to be fitted with Schnorchel, which should also be classified as a post-1943 innovation. The idea was not a new one, but its widespread introduction in the summer of 1944 drastically changed the complexion of the antisubmarine war, as was pointed out in previous discussion. Schnorchel must certainly be reckoned with in estimating future trends, and future Schnorchels, equipped with radar camouflage, may be expected to be even more effective than those which the Germans used.

Significant changes were being made at the end of World War II not only in submarine design, but also in weapons for submarine use. The acoustic torpedo discussed in Chapter 15 is the most familiar example.

[a] The hydrogen peroxide required was expensive to produce and the majority of the supply was used by the German Air Force especially in the V-bomb program.

but there were other developments as well. Long-range and zigzag torpedoes were introduced for use against convoys, considerably increasing the probability of hit. Fortunately few U-boats had opportunities to fire them. The Ingolene torpedo, with the Walter turbine propulsion giving long range and high speed, was developed but not put into operational use. Such weapons may be expected to increase the potential effectiveness of submarines in the future.

On the Allied side end-of-war developments were mostly of the nature of improvements to existing craft and weapons, since they were operating with good success. New types of sonar for improved detection and attack were under consideration, in particular scanning sonar which gave an instantaneous plan position indicator plot of target position. More effective attack weapons were under development, and the recently introduced Squid gave evidence of having a probability of success in attacks about ten times that of ordinary depth charges.

Certain more general developments will also undoubtedly have profound effects on future antisubmarine warfare, just as sonar, radar, and the aircraft profoundly affected it during World War II. Atomic explosives and power utilizing nuclear energy come immediately to mind as the most revolutionary of recent introductions. It is impossible to estimate the effects of such developments now, all that can be done is to point out that they are likely to be considerable. Somewhat less striking, but also of great importance, are the very extensive developments of guided missiles. Homing torpedoes may be considered as a particular class of weapons of this type.

What, then, are we to conclude that the future of submarine and antisubmarine operations will be like. Some conclusion is in order even though we recognize that it can only be a wildly speculative one.

The whole state of naval warfare in the future is uncertain, but it can surely be agreed that control of the sea, including the depths beneath the surface and the space above it, is of prime military importance, and such control may rightly be considered as the objective of naval power. How such control may best be accomplished is a question for future analysis and planning to decide. The general means available are naval craft and missiles: for modern warfare, no longer a matter of personal combat, is based on the missile, the means of implanting a destructive agent in the enemy's midst from long range. Naval craft—ships, aircraft, and submarines—are fundamentally missile-carriers whose aim is to launch missiles so that they reach the proper place.

The characteristics of each type of craft are determined in part by the requirements of the missile which it launches. In part, however, they are intrinsic speed, endurance, and maneuverability. Relative ease of detecting the enemy and being detected by him are also of great importance.

In the past submarines have been built around the torpedo as missile. Improvements in torpedo design and the possible introduction of submarine-launched guided missiles may significantly alter its role in the future. The great intrinsic advantage of the submarine is its invisibility, in which it still exceeds all other types of craft. Means for overcoming this invisibility are likely to remain the chief concern of antisubmarine measures. Their detailed nature must, however, be determined in terms of the use to which submarines are put and of the type of submarines involved.

A satisfactory estimate of the most probable enemy use of submarines can hardly be made without first deciding on the general tactical and strategical situation which is likely to exist. We should first determine who will be fighting whom, what bases and facilities each will have, what supply lines or other objectives are open to enemy submarine attack. Setting up such a complete problem is, however, beyond the scope of this discussion, but we can still make some predictions in general terms.

In the first place it is reasonable to expect that submarine tactics which proved to be highly effective in World War II will be tried again in the future. In particular the use of submarines to attack merchant shipping is likely to be repeated by our enemies so long as our strategy is dependent on such ships. In any major war this is likely to be the case, since we will use ships to supply bases outside the continental United States and to import necessary materials of war. Only if the enemy expected to win such a rapid and crushing victory as to make destruction of our shipping unnecessary would he be expected to ignore the importance of a submarine campaign against merchant ships.

The developments of the last period of World War II support this point of view. The new types of German U-boats which were designed and constructed after 1943 were intended for the same basic purpose as the earlier ones—to attack merchant ships. No

major change was envisaged, but it was hoped that the increased U-boat speed would restore their tactical advantage and permit them to resume effective attacks against convoys, even when operating submerged to gain safety from aircraft.

The use of submarines for antishipping operations involves use of the torpedo as the primary weapon. New developments suggest, however, that different weapons, such as a guided missile of the V-bomb type, might also be launched from submarines. If such a missile were designed to carry nuclear explosives, the destructive power of the weapons which even a relatively small submarine could carry would be many times greater than that of a battleship or carrier at present. Weapons might well be launched with accuracy comparable to that of present gunnery or bombing. Since the submarine is an all-but invisible craft, developments of this sort might be expected to be extremely effective.

The detailed evaluation of the effectiveness of possible types of future submarine operations is beyond the scope of this discussion and could not be made now in any case. It is first necessary to determine the fundamental capabilities of the craft and missiles that may be involved, with all possible new developments and improvements. When this has been done the tactical evaluation can be undertaken.

It does appear, however, that future developments are not likely to eliminate the submarine's great merit, its relative invisibility. At the same time the striking power of submarines is likely to increase. We may safely conclude that submarine and antisubmarine warfare will be highly important phases of any future naval conflict.

AGREEMENT BETWEEN ALLIED ASSESSMENTS OF ATTACKS ON U-BOATS AND THE RESULTS REVEALED AT SURRENDER

At the end of World War I it was found that the number of U-boats which had actually been sunk was rather less than the number presumed sunk according to the assessment list. At the start of World War II it was intended that the assessment policy be a little more realistic, and more convincing evidence was demanded to secure an assessment of "sunk" (A) or "probably sunk" (B).

The Italian surrender was followed by the publication of a list of the Italian U-boats which did not return to base prior to the armistice. When compared with the Allied assessments for attacks thought to have been made on Italian U-boats the agreement was excellent. There were 72 A and 7 B assessments, a total of 79 Italian U-boats sunk or probably sunk, whereas the Taranto list showed 80 submarines to be missing. Furthermore intelligence had provided the names of 67 of them before the armistice, and these names all checked.

The German surrender provided a list of the U-boats lost with the name of the commander and date and position of the sinking. A comparison of the A and B assessments and the losses shown in the German list follows:

Allied assessments compared with German list *

		A	*B*	*Total*	*German list*
I	Sept. 39–June 40	21	0	21	21
II	July 40–Mar. 41	13	7	20	13
III	Apr. 41–Dec. 41	26	1	27	27
IV	Jan. 42–Sept. 42	27	23	50	50
V	Oct. 42–June 43	79	49	128	141
VI	July 43–May 44	117	79	196	206
VII	June 44–May 45	105	54	159	179
	Sept. 39–May 45	391	213	604	643

* These data are based on information available at V-E Day. Neither Allied nor German information is complete for the last periods. Hence the figures given here do not agree in detail with those presented in Chapter 8, based on more complete records available several months later. Nevertheless the agreement of Allied and German estimates proves the overall accuracy of the assessments made during World War II.

It is clear that the Germans lost more U-boats as a result of Allied action at sea than the combination of A and B assessments would indicate. This is to be expected as losses due to mines, or perhaps ordinary hazards of the sea, would not be known to the Allies. In only one of the periods did the total A and B assessments exceed the losses given in the German list. For this period, July 1940–March 1941, there were 7 B assessments which have never been confirmed as sinkings though intelligence has completed the story of the sinkings for this particular period. The percentage of B assessments which actually corresponded to sinkings is problematical, but those cases which do not represent sinkings are compensated for by lower assessments which actually represented sinkings though they were not credited as such.

A survey of the attacks on Japanese U-boats shows 38 assessments of A and 62 B assessments, a total of 100 A and B. The individual losses from Japanese lists add up to 123, of which two were from mines and two by running aground. The agreement is not as good as with the Italian and German lists, but it is still satisfactory, particularly when the greater difficulty of obtaining intelligence is considered.

The A and B assessments for the losses by the three Axis powers are given below and a significant difference is obvious.

	A	*B*	*Total*	*Enemy Loss Lists*
Italian	72	7	79	80
German	391	213	604	643
Japanese	38	62	100	123
	501	283	783	846

The ratio of A to B assessments is very high for Italians, intermediate for Germans, and low for the Japanese. This relationship would seem to be due to at least three main factors:

1. The Italians gave up easily, surfaced, and surrendered, thus giving sure proof of destruction, whereas the Japanese seldom surfaced when the game was up.

2. Intelligence information was easier to obtain from European sources than from Japanese.

3. Antisubmarine forces in the Pacific had less opportunity to remain in the vicinity to search for evidence of destruction because of other fleet duties.

The complete picture for World War II allows the conclusion that the summation of A and B assessments for attacks on Axis U-boats gives a total which

is close to that of the actual losses and useful for practical purposes. Attempts to correlate B attacks with the loss of individual U-boats were not always successful and showed that the validity of any particular B assessment as evidence of the destruction of a U-boat is questionable.

GLOSSARY

ACES. U-boat commanders of outstanding records, credited with sinking large amounts of Allied shipping.

ACOUSTIC TORPEDO. A torpedo which detects the target ship by means of sound and is controlled by this sound so as to steer towards the ship and eventually hit it.

ADMIRALTY. The headquarters staff of the British Navy. Also used in the same sense for German Navy as "German Admiralty."

AHEAD-THROWN. (A) Weapon: an antisubmarine weapon used by surface craft which is projected ahead of the ship, usually to a distance of about 300 yd; (B) attack: an attack employing an ahead-thrown weapon.

AIMING ERRORS. Errors in aircraft attack arising from inaccuracies in dropping bombs, or firing rockets, i.e., errors in aiming the weapon.

A.N.D. Admiralty Net Defense: a net suspended along the sides of a ship to catch torpedoes.

APPROACH ERROR. Error in surface craft antisubmarine attack which would exist without submarine evasion. *See* ATTACK ERROR and EVASION ERROR.

ANTISUBMARINE ATTACK PLOTTER [ASAP]. An electronic device for plotting positions of own ship and submarine during attack. Sonar echoes are plotted automatically on a large cathode-ray tube of long persistence.

ANTISUBMARINE SHIP. Any naval ship used for attacking submarines, i.e., destroyers, destroyer escorts, frigates, sloops, corvettes, trawlers, patrol craft [PC], sub chasers [SC], suitably equipped minesweepers, etc.

ASDEVLANT. Anti-Submarine Development Detachment, Atlantic Fleet; an organization set up to test and develop antisubmarine equipment and tactics for its use.

ASDIC. British echo-ranging sound gear, equivalent to United States sonar. Name is derived from Anti-Submarine Detection Internal Committee, which pioneered the development of such equipment.

ASG (RADAR). United States Navy airborne S-band (10-cm) search radar, introduced early in 1943.

ASSESSMENT. An estimate of the damage done to a U-boat resulting from an attack by an antisubmarine craft. This estimate is made by a special committee on the basis of all available evidence. Assessments range from "A"—U-boat known to be sunk, to "I"—attack not on a U-boat.

ASV. Air-to-surface-vessel radar, that is, airborne radar for searching for surface ship targets.

ASWORG. Anti-Submarine Warfare Operations Research Group. A group of civilian scientists attached to Tenth Fleet Headquarters. Later known as ORG when transferred to COMINCH Headquarters.

ATTACK. Release of one or more weapons against a U-boat in a barrage or stick. Several attacks made in succession on the same U-boat (i.e., within a few hours of each other) are called an incident, but the term attack is sometimes used loosely as synonymous with "incident."

ATTACK ERROR. Distance between mean point of explosion of weapons and center of submarine. *See* AIMING ERROR, EVASION ERROR, APPROACH ERROR.

ATTACK TEACHER. A mechanical device for simulating the conditions of a surface craft attack on a submarine, used primarily for training personnel on shore.

AVC. Automatic volume control in an electronic amplifier.

BALANCED FORCE. A force capable of an equally effective offensive at all times, in particular, both day and night.

BARRAGE. A number of depth charges or contact charges released as a group in a surface craft attack.

BDI. Bearing deviation indicator, a modification to standard sonar gear giving more accurate bearings by use of lobe comparison.

BIBER. A midget submarine with crew of one, developed by the Germans and used during 1944–45.

BLIND TIME. The time from loss of contact with the submarine (or release of weapons) until weapons reach U-boat depth.

BORKUM. A German radar search receiver of crystal detector type covering the 75- to 300-cm band.

BROWNING SHOT. A torpedo shot fired into a convoy without being aimed at any particular ship.

CAMOUFLAGE (RADAR). Any device for reducing the range at which an object can be detected by radar, for example, nonreflecting coatings for reducing echoes.

CAM SHIPS. Merchant ships fitted with catapults for launching aircraft.

CATALINA [A C]. Twin-engined seaplane (or amphibian) built by Consolidated Aircraft. Long range, but slow, with moderate bomb load.

CLASS A ATTACK. An aircraft attack on a submarine in which bombs are dropped not more than 15 sec after the submarine submerges.

COASTAL COMMAND. The branch of the British Royal Air Force responsible for ocean patrol and attacks on naval targets.

COMMANDED VOLUME. The locus of points about an exploding charge or bomb (or about its trajectory) that have the property that a submarine with center at any of the points will be sunk.

COMMODORE (OF CONVOY). A senior naval officer (or occasionally merchant captain) responsible for the navigation, signalling, and other such activities of the convoy. The escort commander, on the other hand, is responsible for its defense against the enemy and has ultimate authority.

CONTACT. An instance of detection of an enemy unit. For example, when a U-boat sights a convoy it is a contact on a convoy, as when an aircraft receives a radar blip from a submarine, it is a contact on a submarine.

CONTACT FUZE. A device in a bomb, rocket, or other projectile for causing it to explode on hitting the target.

CONVOY. A group of merchant ships sailing together, usually defended by naval ships acting as escorts.

COORDINATED ATTACK OR INCIDENT. An attack or incident in which two or more ships and aircraft (or both ships and aircraft) take part. *See* ATTACK and INCIDENT. Those involving both ships and aircraft are sometimes termed joint attacks (or incidents).

CORVETTE. A small antisubmarine ship, usually capable only of rather slow speed.

COTCLANT. Commander Operational Training Command, Atlantic Fleet, in charge of training for the Atlantic Fleet.

COUNTERATTACK. An attack on a submarine which has attacked friendly ships or is threatening to do so.

COUNTERMEASURE. Any action or device designed to reduce the effectiveness of some enemy action or device. Tactical countermeasures involve changes in tactics or operational procedures. Material countermeasures involve new equipment. These terms are used most frequently with respect to radar and homing torpedoes.

CNO. Chief of Naval Operations—the naval officer (and subordinate staff) in charge of the U.S. Navy Department.

CREEPING ATTACK. A coordinate attack by surface craft aimed at surprising the submarine. An "assisting ship" maintains sonar contact and directs the "attacking ship," which proceeds at slow quiet speed over the submarine without echo ranging and drops charges.

CUBA IA. Antenna used with the German Tunis search receiver for S-band reception, made up of dipole and parabolic reflector.

CURLY. A torpedo which follows a zigzag course.

DB. Decibel. A unit of sound intensity. See any textbook of general physics or acoustics.

D-DAY. Day of invasion of Normandy—June 6, 1944.

DENSITY. Number of objects per unit area. For example, U-boat density might be expressed as the number of U-boats per million square miles of ocean.

DEPTH FUZE. A device for detonating a bomb or other weapon at a preset depth.

DESTROYER ESCORT [DE]. A large antisubmarine ship (about 1,800 tons) of fairly high speed, about 18–24 knots.

DF. Radio direction finding by intercepting enemy radio transmissions and obtaining their bearings with directional receivers, thereby estimating the enemy position. *See* HFDF.

DIRECT HIT (by torpedo). A direct hit is made by an acoustic torpedo on a ship using a noisemaker if the torpedo, while steering toward the noisemaker, hits the ship.

DISPERSION (of bombs). The variation that would exist in the explosion points of a large number of bombs of a given type if they were all dropped under the same conditions (in so far as conditions could be controlled).

DIVERTER. A device for causing a towed noisemaker to tow at one side of the ship's wake rather than directly astern.

ELEKTRASONNE. German code name for a system of radio beacons used as navigational aids.

ESCORT. A naval ship or aircraft used to protect a merchant ship or group of ships. Antisubmarine ships are sometimes termed escorts even when engaged in offensive operations.

ESCORT CARRIER [CVE]. A small aircraft carrier usually built on a merchant vessel hull and designed to fly antisubmarine planes. Escort carriers were actually used mostly in offensive operations, only infrequently on escort duties.

ESCORT COMMANDER. Naval officer in command of forces assigned for defense of convoys.

ESCORT GROUP. A group of antisubmarine ships which are operated as a unit.

EVASION ERROR. Error in antisubmarine attacks introduced by evasive maneuvers on the part of the submarine.

EVASIVE ROUTING. Routing to avoid known submarine positions.

EXCHANGE RATE. Ratio of merchant vessels sunk by submarines to submarines sunk by antisubmarine vessels.

FAT. German designation for a torpedo which runs a zigzag course, with nature of a zigzag not adjustable. *See* LUT.

FERRET. An aircraft equipped with receivers for monitoring enemy radar transmissions.

FLEET AIR ARM. British carrier and ship-based aircraft.

FLEET AIR WING 7. This air wing was based in Britain until the end of World War II.

FLIEGE. German code name for S-band antenna of Tunis GSR. *See* CUBA IA.

FLIP-FLOP CONTROL. Rudder control for a homing weapon which can be only in central position or hard over port or starboard.

FLYING FORTRESS. A four-engine Boeing bomber used to a small extent for antisubmarine patrol.

FOLLOW-UP (of contacts). Effort to gain contact with a submarine whose position was accurately known at an earlier time by virtue of a previous contact.

FOURTH FLEET. United States naval forces which were based in the South Atlantic; a subdivision of the Atlantic Fleet.

FOXER. British towed noisemaker gear for decoying German acoustic torpedoes, consisting of two parallel bar noisemakers and diverters. Near the end of the war UNIFOXER, a single noisemaker, was employed. *See* FXR.

FRIGATE. A large British antisubmarine ship (about 2,000 tons) of long endurance but moderate speed, 15–18 knots.

FXR. United States single towed noisemaker of parallel bar type (*See* FOXER).

GAMBIT. An aircraft search for follow-up of contacts in which the aircraft leaves the most probable initial submarine position and flies at some distance from it for some time, in the hope that the submarine will return to the surface where it can be sighted when the aircraft returns to the area.

GAP, MID-OCEAN. The mid-ocean area which could not be patrolled by land-based aircraft.

GLIDER BOMB. German radio-controlled glider bomb which is guided to target by parent aircraft.

GNAT. German Navy acoustic torpedo which homes automatically on noise from target ship.

GROSS TON. A measure of ship size based on volume. The tonnage is the entire internal cubic capacity of the ship expressed in tons of 100 cubic feet to the ton, except certain spaces which are exempted, such as peak and other tanks for water ballast, open forecastle bridge and poop, anchor gear, steering gear, wheel house, galley, and cabins for passengers.

GSR. German search receiver, i. e., German radar receiver for detecting transmissions by Allied search radar.

GU. Designation for convoys from Mediterranean and Gibraltar to the United States GUS for slow convoys, GUF for fast.

GUIDED MISSILES. A missile whose course can be adjusted after launching (or firing) so as to hit the target. The adjustment may be made by an operator in the launching craft or may be automatic. Acoustic torpedoes are examples of the latter type.

HALIFAX. A British four-motored heavy bomber built by Handley-Page.

HEDGEHOG. An ahead-thrown weapon with mortar projected barrage of 24 contact charges, trainable to about 20 degrees off the bow of the ship.

HFDF. High-frequency DF (*see* DF). Frequencies of about 10 megacycles are involved.

HG. Designation for convoys from Gibraltar to the United Kingdom.

HOLD-DOWN HUNT. A search of sufficient intensity to insure the submarine's being sighted if it surfaces.

HOMING. Guiding to a source of signals. A U-boat in contact with a convoy unit's signals, thereby homing other U-boats to the scene. An acoustic torpedo steers towards the sound from a ship's propellers, thereby homing on the target.

H_2S. High resolution radar of S-band frequency for use in blind bombing.

HUDSON. Twin-engine Lockheed bomber.

HUNTER-KILLER OPERATIONS. Offensive operations aimed at finding and destroying U-boats, usually involving groups of surface craft and sometimes coordinated with aircraft.

HX. Designation for convoys from Halifax or New York to Britain.

H_2X. High resolution radar of X-band frequency for use in blind bombing.

HYDROPHONE. A receiver of underwater sound.

INCIDENT. *See* ATTACK and COORDINATED INCIDENT.

INDIRECT HIT. A hit made by an acoustic torpedo which is attracted to the target ship out of a trajectory leading to a noisemaker.

INFLUENCE (fuze or pistol). A fuze activated by the change in earth's magnetic field due to the submarine's presence, which is designed to detonate the charge whenever it is close enough to the submarine to be effective.

INTERCEPT RECEIVER. Radar search receiver (*see* GSR).

JAUMANN ABSORBER. A nonreflecting covering which is effective against S- and X-band radars, made up of spaced layers of semiconducting paper. *See* WESCH ABSORBER.

LATERAL RANGE CURVE. A curve which gives the probability of detection of an object by a searcher (who is proceeding on a straight course) as a function of distance of direct approach.

LEIGH LIGHT. British aircraft searchlight used for night attacks.

LETHAL AREA. The area on the ocean surface centered above an exploding depth bomb which has the following property: In a Class A attack any submarine whose center lies below the lethal area may be considered sunk, and no others.

LETHAL RADIUS. The lethal radius of a given explosive charge is the maximum distance from the pressure hull at which it may be expected to do lethal damage.

LIBERATOR. Four-motored heavy bomber built by Consolidated Aircraft frequently modified for use in antisubmarine patrol because of its long range and large bomb load.

LIFE (LIFETIME) OF A U-BOAT. At any time the average life of a U-boat is the number of U-boats at sea divided by the rate at which U-boats are sunk per month.

LIMITING APPROACH LINES. The boundary of the region from which a submarine can approach a ship or formation, drawn relative to the ship or formation.

LINE ERROR. The component perpendicular to the course of attacking aircraft of the distance between center of stick and center of submarine.

LOCALIZATION. Determination of exact submarine position by sonar.

LOST CONTACT (RANGE). Range at which sonar contact with submarine is lost because submarine is below sonar beam.

LUT. German designation for a torpedo which runs a preset zigzag course. *See* FAT.

MAC SHIPS. *See* CAM SHIPS.

MAD. Magnetic anomaly detector (or magnetic airborne detector), an aircraft instrument for detecting distortion of the earth's magnetic field due to the presence of a submarine.

MAXIMUM SUBMERGENCE. Submarine tactics which involve remaining submerged as much as possible. Normally about 2 to 4 hours a day must be spent surfaced or at Schnorkel depth.

MEAN RADIAL ERROR. Average distance from center of target to center of barrage.

METOX. Early GSR for long wavelength radar, introduced in 1942.

MK II RADAR. British long wavelength search radar used on aircraft.

MK III RADAR. British airborne S-band search radar.

MK 8 DEPTH CHARGE. United States influence-fuzed depth charge.

MOSQUITO. British twin-engined fighter-bomber built by De Haviland.

MOUSETRAP. United States ahead-thrown weapon with rocket projected barrage of 8 or 16 contact charges. Used in small ships.

MPI. Mean point of impact of a group of bombs.

Mucke. Horn antenna for X-band reception with Tunis GSR.

MV. Merchant vessel.

Naxos. (1) Early nondirectional GSR effective in S-band; (2) Amplifier used in Tunis GSR.

NM. Noisemaker.

Noisemaker. An artificial source of underwater noise used to conceal the noise made by a ship or submarine or to interfere with the operation of, or to decoy, acoustic devices such as acoustic torpedoes.

North Russian Convoys. Convoys from Britain around the north of Norway to Murmansk, Archangel, or other North Russian ports, and returning convoys.

OB. Designation used in early years of war for convoys outward bound from Britain for America and Africa.

Observant. A search plan used by surface craft, consisting of going to point of last contact with submarine and then steaming around a square centered at that point with 2-mile sides.

OG. Designation for convoys from Britain to Gibraltar.

ON. Designation for convoys from Britain to America. During latter part of World War II ON was reserved for 9-knot convoys, ONS being used for 7-knot.

ORG. Operations Research Group. *See* ASWORG.

ORS. Operations Research Section, title of British operations research organizations. Most frequently used in ORS CC Operations Research Section, Coastal Command.

OS. Convoy designation for convoys from Britain southbound to Sierra Leone.

Patrol Craft. Small antisubmarine craft, normally not over about 200 feet in length.

PQ. Designation for convoys from Britain to Archangel. (*See* North Russian Convoys.)

Practice Attacks. Simulated attacks carried out either on the attack teacher or in exercises with a friendly ("tame") submarine.

Proximity Fuze. A fuze designed to detonate a bomb, charge, or projectile, when within a certain distance of the target. (*See* Influence Fuze.)

P/W. Prisoner of war.

Q Attachment. British auxiliary sound gear with beam directed below the main Asdic beam for maintaining contact with deep U-boats at short ranges.

R600. Same as Metox.

Range Errors. The component parallel to the source of attacking aircraft of the distance between center of stick and center of submarine.

RDF—Type 286, Type 271. British surface craft search radar. Type 286 had fixed aerials and operated on long wavelength. Type 271 was S-band gear with rotating beam and PPI presentation.

Retro-Bombs. Contact bombs used by aircraft in conjunction with MAD. Bombs are propelled backwards by rocket motors so as to drop vertically from aircraft.

Reverberation. The totality of small false echoes received on sonar from objects in the ocean, its surface and the bottom.

Rocket. Used alone the word implies forward-firing rockets of about 3-in. diameter used by aircraft. (*See* Mousetrap, for comparison.)

Rundfunk. Submersible GSR aerial used for long wavelength radar reception.

S-Band. Radar operating band for wavelengths of about 10 cm.

SBT. Submarine bubble target. A German decoy used to produce false echoes from a cloud of bubbles.

SC. Designation for 7-knot convoys from America to Britain.

Schnorkel. U-boat combination air intake and Diesel exhaust, permitting operation on Diesels when at periscope depth. Introduced in 1944.

SCR-517. United States Army S-band airborne search radar.

SCR-717. Improved version of SCR-517.

SD Radar. United States Navy X-band airborne search radar.

Sea Return. The totality of false radar echoes from ocean surface.

Search Receiver. A radar receiver for intercepting signals from enemy search radar and thereby being warned of his approach.

Sensitivity Pattern. The sensitivity of an acoustic torpedo is a diagram showing the range and bearing at which a given sound source will produce a given signal at the torpedo control mechanism.

SG. United States Navy surface craft S-band search radar (*see* RDF, Type 271).

Shadowing. A U-boat shadowing a convoy kept in contact with it and reported information about it without attacking.

Sinking Rate. The effectiveness of a U-boat in sinking ships. The sinking rate is equal to the U-boat's sweep rate times the fraction of ships contacted that are sunk.

SL. (1) Convoy designation for convoys from Sierra Leone to Britain; (2) radar designation for United States Navy radar similar to SG but lighter in weight.

Sloop. Large antisubmarine ship of moderate speed, similar to frigate.

Sonar. The United States Navy term for underwater sound equipment and its use. British use "Asdic" in similar way.

Sonobuoy, Expendable Radio. A small buoy capable of transmitting sounds heard in the ocean to an observer by radio. Used primarily by aircraft.

Sortie. An aircraft flight.

Squid. An ahead-thrown depth charge and associated depth-determining sound gear by means of which the submarine's actual depth is automatically set into the depth charge fuze.

STEP-ASIDE. A radical zigzag designed to permit a ship to approach a U-boat with minimum danger from acoustic torpedoes.

STERN CHASE. An attack or pursuit course which overtakes the target from its stern.

STICK. A number of bombs or depth charges dropped in a row.

STRAGGLER. A ship which left a convoy because unable to maintain proper speed.

SUBMERGED APPROACH ZONE. The area around a convoy from which a submarine can make a submerged approach to it.

SUNDERLAND. British four-motored seaplane.

SUPPLY U-BOAT. A U-boat fitted to refuel and supply other U-boats without attacking any ships itself.

SUPPORT GROUP (i.e., 2nd Support Group). A number of antisubmarine ships kept together permanently as a group to hunt U-boats and provide extra defense to convoys threatened by attack.

SWEEP RATE. The number of contacts made per hour per unit of target density by a searching craft. It is expressed in square miles per hour and is the measure of searching craft's effectiveness of covering area.

SWEEP WIDTH. Sweep rate divided by speed (approximately).

T-5. German acoustic torpedo (earliest models were designated T-4).

TENTH FLEET. United States Navy Headquarters assigned tasks of conducting war on submarines and protecting merchant shipping.

TORPEDO DANGER ZONE. Area around a ship or convoy from which a submarine has a good chance of hitting with a salvo of torpedoes.

TORPEX. Recently developed explosive superior to TNT in destructive power.

TOSS BOMBING (or ROCKETING). A method of glide-bombing (or rocket-firing) in which weapons are released as the plane pulls out of the glide.

TRACKING. Maintaining contact with an enemy unit so as to determine its course and speed.

TRACTRIX. The curve of pursuit followed by always proceeding towards an object which is itself moving with constant course and speed.

TRANSIT, TRANSIT AREA. Passage of a submarine from base to its operating area is termed a transit and the area between base and the operating area is the transit area.

TUNIS. Directional GSR for interception of S-band and X-band radar. (*See* NAXOS, MUCKE, and FLIEGE.)

TYPE XVII-B U-BOAT. Small experimental U-boats with oil-H_2O_2 turbine drive for submerged operations having speeds up to 21 knots.

TYPE XXI U-BOAT. New type U-boat with powerful electric motors, and extra batteries permitting high submerged speed operation (up to 15 knots).

TYPE XXIII U-BOAT. Similar to Type XXI, but smaller, for coastal operations.

TYPE XXVI U-BOAT. Proposed ocean-going U-boat with turbine drive as in Type XVII.

TYPE 147B ASDIC. British sound gear used for determining submarine depth during an attack.

TYPE 271 RADAR. British shipborne 10-cm search radar.

U-BOAT. Any enemy submarine of 200 tons or larger.

UG. Designation for convoys from United States to Gibraltar and Mediterranean; UGS for slow convoys, UGF for fast.

U-KREUZER. Large long-range U-boat.

V-1. German "buzz-bomb" or jet-propelled pilotless aircraft of moderate range.

VLR AIRCRAFT. Very long-range aircraft.

VIXEN. An attenuator for use with airborne radar to reduce the output as range to the target is closed, thereby confusing the GSR operator.

WANZ G-1. Long wavelength GSR, an improvement on Metox.

WEAPON LETHALITY. The effectiveness of a weapon in producing damage, without regard to the accuracy with which it can be placed.

WELLINGTON A C. British two-motored bomber and patrol plane built by Vickers.

WESCH ABSORBER. A rubber-like coating for reducing radar echoes. *See* JAUMANN ABSORBER.

WHITLEY. British two-motored bomber and patrol plane.

WOLF PACKS. Groups of U-boats operating together as a unit.

X BAND. Band of radar frequencies with wavelength approximately 3 cm.

ZIGZAG. Frequent course changes to make attack by submarines more difficult.

CONTRACT NUMBERS, CONTRACTORS, AND SUBJECT OF CONTRACTS

Contract Number	Name and Address of Contractor	Subject
OEMsr-20	The Trustees of Columbia University in the City of New York New York, New York	Studies and experimental investigations in connection with and for the development of equipment and methods pertaining to submarine warfare.
OEMsr-1128	The Trustees of Columbia University in the City of New York New York, New York	Conduct studies and experimental investigations in connection with and for the development of equipment and methods involved in submarine and subsurface warfare.

The projects listed below were transmitted to the Executive Secretary, NDRC, from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

SERVICE PROJECT NUMBERS

Service Project Number	*Subject*
AC-50	Operations research
NR-150	Operations research

INDEX

The subject indexes of all STR volumes are combined in a master index printed in a separate volume. For access to the index volume consult the Army or Navy Agency listed on the reverse of the half-title page.

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